# DEEP BOREHOLE PLACEMENT OF RADIOACTIVE WASTES

## A FEASIBILITY STUDY

Bernt S. Aadnøy & Maurice B. Dusseault

## Executive Summary

Deep Borehole Placement (DBP) of modest amounts of high-level radioactive wastes from a research reactor is a viable option for Norway. The proposed approach is an array of large-diameter (600-750 mm) boreholes drilled at a slight inclination, 10° from vertical and outward from a central surface working site, to space 400-600 mm diameter waste canisters far apart to avoid any interactions such as significant thermal impacts on the rock mass. We believe a depth of 1 km, with waste canisters limited to the bottom 200-300 m, will provide adequate security and isolation indefinitely, provided the site is fully qualified and meets a set of geological and social criteria that will be more clearly defined during planning. The DBP design is flexible and modular: holes can be deeper, more or less widely spaced, at lesser inclinations, and so on. This modularity and flexibility allow the principles of Adaptive Management to be used throughout the site selection, development, and isolation process to achieve the desired goals.

A DBP repository will be in a highly competent, low-porosity and low-permeability rock mass such as a granitoid body (crystalline rock), a dense non-reactive shale (chloritic or illitic), or a tight sandstone. The rock matrix should be close to impermeable, and the natural fractures and bedding planes tight and widely spaced.

For boreholes, we recommend avoiding any substance of questionable long-term geochemical stability; hence, we recommend that surface casings (to 200 m) be reinforced polymer rather than steel, and that the casing is sustained in the rock mass with an agent other than standard cement. We recommend that canisters be placed in a non-cased basal section of the borehole with buffer (cation adsorbent), sealants (flow blockage), and dense frictional sections (load transfer) separating the canisters. For intermediate- and low-level radioactive wastes, we recommend a similar DBP approach using waste capsules, but the isolation security level (capsule spacing, sealants, borehole interval used) can be adjusted to reflect the lower risk levels.

Percussive drilling mining technology is used for guide holes and large diameter isolation boreholes. The pre-drilled, small-diameter guide hole is also used also for detailed individual borehole qualification. Oilfield technology using wireline and coiled-tubing methods forms the basis of the waste placement and isolation process. Lowering appropriately sized and equipped canisters to hole bottom using modern wireline systems, followed by the placement of buffer, seals and backfill, can be carried out with coiled tubing units.

In summary, the DBP approach has many advantages linked to operational safety, DBP modularity, independent qualification of each borehole, and an unquestioned technical ability to provide seals and buffer material at the borehole scale. Geologically, choosing the best site is a key aspect of the DBP repository concept. From geomechanics, rock physics, and geophysics considerations, based on our mining, oilfield and rock mechanics backgrounds, it is our opinion that finding appropriate sites in Norway is a straightforward task, but it must be a carefully executed program involving many disciplines.

## Acknowledgements

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**Richard E. Jackson**, PhD, PEng, vetted the Report independently. He has a long career in nuclear waste management and geological sequestration for radioactive materials, and this is key to his assessment of this Report. He helped found the firm Geofirma Engineering Ltd. (Ottawa, Ontario) that led the Deep Geological Repository site investigations for Ontario in the period 2005-2015, and the firm was recently awarded (2020) the work program for the next repository site studies for low- and intermediate-level radioactive wastes. Dr Jackson remains active in his retirement and is an Adjunct Professor at the University of Waterloo, Waterloo, Ontario.

## Authors

**Bernt S. Aadnøy**, PhD, PE, is a Professor of Petroleum Engineering at the University of Stavanger, and is also Adjunct Professor at the Norwegian University of Science and Technology (NTNU). He works mainly on all aspects of well engineering, drilling, geomechanics, production and reservoir engineering, smart well technology and automation. Before transiting to academia he worked many years in oil companies, and have strong ties to applied problems. He has published more that 300 articles and have authored or co-authored 8 books, amongst them Modern Well Design, Petroleum Rock Mechanics, Mechanics of Drilling and Multivariate Optimization in Well Engineering. He was editor of the SPE Advanced Drilling and Well Technology book. He holds 15 patents within intelligent well technology.

**Maurice B Dusseault**, PhD, PEng, is a Professor of Geological Engineering at the University of Waterloo, Waterloo, Ontario in the Department of Earth and Environmental Sciences. With strong ties to industry, he pursues subsurface engineering, geophysics and geomechanics issues in the energy and mining sectors. His experience includes oil and gas development, deep slurried granular waste and biosolids injection, $CO_2$ sequestration, energy storage (compressed air, $H_2/CH_4$, or heat), geothermal energy, thermohydromechanical coupling in rock masses, and many related subjects. His research and academic product exceeds 625 published papers in Journals and good quality Conferences, as well as two textbooks co-authored with Dr J.A. Franklin. He holds many patents, has supervised over 100 graduate students, and has generated six technically-oriented start up companies in his career.

# Contents

# Chapter 1: Deep Well Scenario

## 1.1 Introduction to Deep Well Scenario

The London convention from 1972[1,2] declared that the sea should not be used for storage of man-made materials from an environmental perspective. The radioactive waste for commercial and research reactors must therefore be placed on land in an acceptable repository.

The mining industry is well established but is usually focused on shallower depth larger-diameter boreholes, or on slim holes for mineral exploration. The offshore oil industry, on the other hand is usually involved in drilling deep wells (3-7 km) in soft sediments with high pore pressures. Since the commodity is petroleum, fairly advanced tools, technologies, methods and equipment exist to facilitate the extraction of valuable hydrocarbons from challenging, often almost inaccessible locations. During this process, a great deal of knowledge is brought to bear, in addition to the additional geological knowledge generated during the exploration and development phases. Also, these oil and gas industry drilling and exploitation processes are well-established in a cost-effective way, where problem reduction is a key issue at all stages.

Depositing radioactive waste in deep onshore wells is not so established from a mining perspective but falls more within the experience of drilling for petroleum. Obviously, modifications have to be done to fit the technology for a new purpose, but oil drilling technology will form the backbone of drilling repository wells and for placement and isolation of radioactive waste.

This chapter will review deep wells as a reference model for developing plans for radioactive waste isolation. We emphasize here, and repeatedly throughout this report, that the oil and gas drilling and well management industry is a valuable knowledge source that can play a key role in the development of a secure repository based on deep wellbore placement.

## 1.2 Review of Construction of Deep HPHT Wells

The objective of this chapter is to review the cost and construction of a deep well in the Oil and Gas (O&G) industry to find and produce hydrocarbons. This technology and cost structure will be used as a reference to assess the construction of a deep borehole[3] array for the placement of radioactive materials. There are advantages beyond the technical and cost aspects to the use of

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[1]http://www.imo.org/en/

[2]https://www.canada.ca/en/environment-climate-change/corporate/international-affairs/partnerships-organizations/marine-pollution-dumping-waste-london.html

[3] A 'well' or 'wellbore' is intended to produce or inject fluids (oil, water, gas). A deep borehole for radioactive waste storage is not a well; the term 'borehole' is correct.

deep boreholes for waste placement, and to access and assess O&G well technology as an important reference technology. O&G wells are logged in considerable detail using cuttings, drilling data, geophysical borehole logs, drilling mud analysis, and are monitored continuously during the deep drilling process. This information helps assess the quality of the rock, which is important for risk assessment for evaluation of leak potential away from the borehole, or the influx of unwanted fluids (high-pressure water or hydrocarbons). Figure 1-1 shows the plan for drilling a 5000 m deep High Pressure-High Temperature (HPHT) well. The relevance to radioactive waste disposal of HPHT technology is its clear high degree of risk mitigation in challenging conditions. Although a waste placement operation in crystalline rock will never encounter such extreme conditions, some of the technologies associated with HPHT wells might be adopted to achieve a higher security level. Furthermore, the diameters and depths of the uppermost casing strings in a HPHT well are similar to the geometric parameters suggested herein for waste canister placement.

A simple summary of the information given in Figure 1-1 is as follows:

- Geological data
    - Lithostratigraphy (rock type and disposition in the geological column)
    - Lithology (rock type versus depth). Here, the upper part is shale or mudstone, at intermediate depth is chalk ($CaCO_3$), and the reservoir at the bottom is sandstone.
- Geomechanical data
    - Overburden stress (weight of the overburden per unit area)
    - Pore pressure in the fluids in the rocks
    - Fracture pressure (borehole strength) for weak and strong intervals, a measure of the minimum compressive stress at that point
    - Leak-off data from other (off-set) wells are recorded fracture pressures from tests previously performed in those off-set wells
- Well and drilling data
    - Casing depths
    - Mud weights used
    - Extensive drilling data (detailed below)

All the parameters listed above are coupled and need to be seen in a common, integrated context. One key parameter is the mud weight used during drilling an O&G well. This is critical to minimize risk of wellbore instability problems such as wellbore collapse and wellbore fracturing leading to loss of drilling fluid to the formation. During drilling, mud losses (lost circulation or wellbore “ballooning”) often occur and are rectified before drilling continues to assure safety.

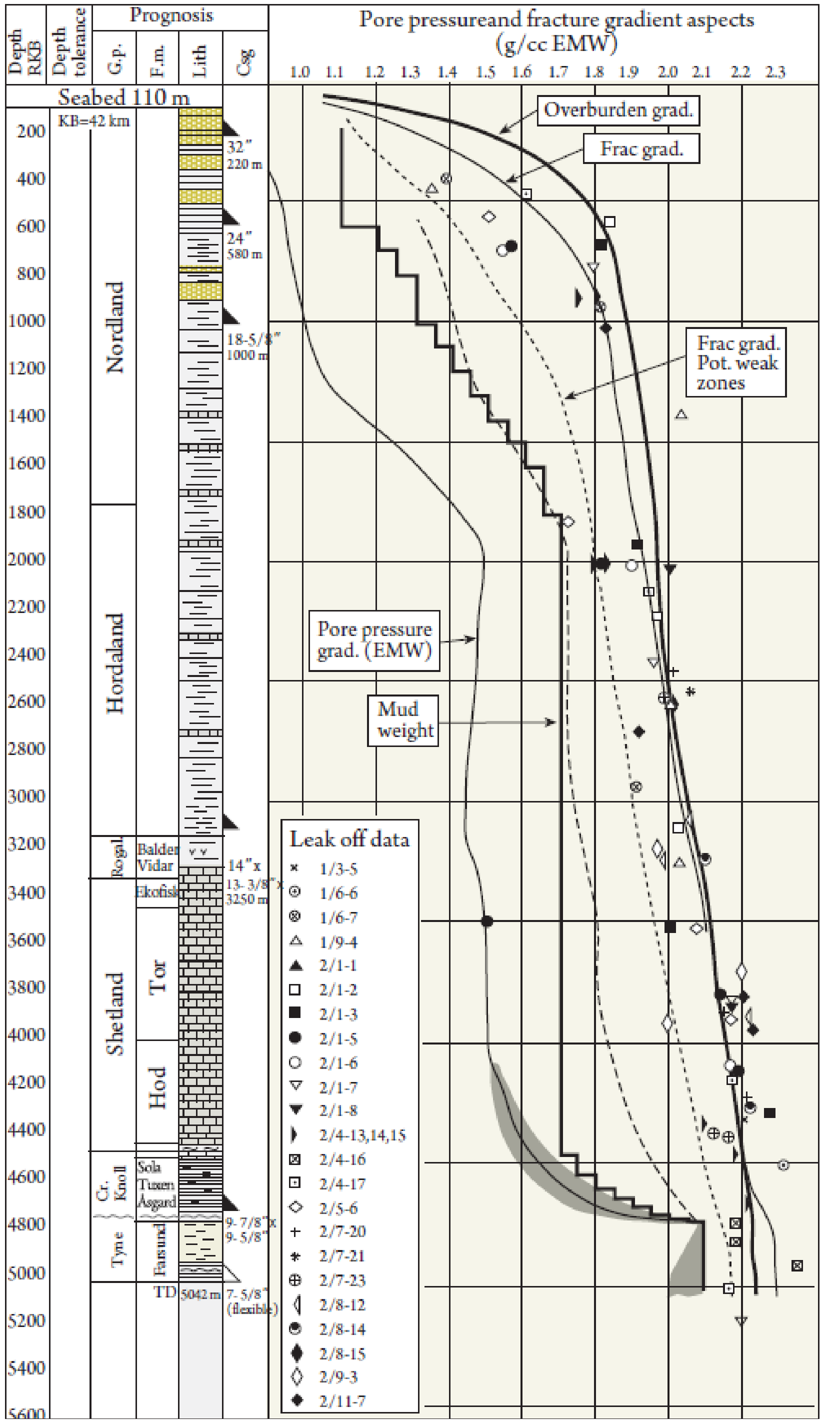


*Figure 1-1: Pressure gradient design prognosis for deep HPHT well offshore the North Sea. (Aadnøy, 2010))*

During the drilling process, many types of well logs are run to determine transitions from one formation type to another and to determine physical properties of the strata. These logs may be compiled while drilling (mud logs, d-exponent logs, mud gas measurements, downhole measurement-while-drilling data…), or are taken using geophysical wireline tools lowered down the borehole when the pipe is removed from the hole. Also, drill cuttings, mud samples, and gas samples are collected and used or preserved for geological analysis (e.g., isotopic analysis of gas). Some of the common well logs are:

- The d-exponent determines the drillability of the rock and is calculated as a continuous log with depth from the real-time drilling data (bit size, weight-on-bit, penetration rate).
- The gamma-ray log discriminates between radioactive clays in shales and clayey rocks, and low- or non-radioactive sandstones, limestones, anhydrites and salt. Advanced radioactivity logs can discriminate between thorium, uranium and potassium ($^{40}K$).
- Sonic logs come in many varieties with different emitter and sensor arrays, and have many uses and interpretations within rock physics, stress and pore pressure analyses, even to the point of rock fabric analysis (fractures) around the borehole vicinity.
- The resistivity log discriminates between oil and water on the basis of electrical conductivity measurements between differently spaced electrodes.
- Focused resistivity logs can determine the degree of formation fluid displacement by drilling mud fluids, and thereby give a rough estimate of strata permeability.
- The density log (or gamma-gamma log) measures the average bulk density of the rock in the borehole wall.
- The caliper log measures the diameter of the wellbore and identifies zones where wellbore stability is marginal (breakouts and washouts in the borehole wall). Multiple-arm and 4-arm caliper logs permit borehole ellipticity to be measured and break-outs and other features to be identified.
- The FMI log gives a picture of the wellbore wall identifying geological peculiarities (joint traces, bedding…), based on arrays of very closely spaced electrodes to map resistivity in the borehole wall.
- Rotating ultrasonic scanning logs can measure the borehole wall geometry with high precision to help identify the details of joint traces, break-out geometry, and ellipticity.

Modern Measurement-While-Drilling (MWD) systems can also measure formation pressure and take reservoir fluid samples without withdrawing the drill pipe, and this information becomes part of the wellbore information package.

During drilling of deep wells, drilling problems often arise; but the end result is often one of the two below:

- *Stuck pipe*. This can be caused by wellbore instability, differential sticking of the drill string against the open borehole wall, or incomplete cleaning of the wellbore which then becomes packed off with drilled cuttings or sloughing formations. If severe, the drill pipe in such a case is cut at depth, the well just above the cut pipe is plugged back, and a sidetrack well is drilled from a shallower level.

- *Circulation losses*. There are cases where a considerable amount of drilling mud is lost to the formation, often when the mud weight is so high that it overcomes the smallest earth stress and the drilling fluid fractures the formation. These are referred to as 'lost circulation zones'. Because the mud weight is higher than the reservoir pore pressure, such losses can lead to a blowout from the reservoir if the mud pressure cannot be sustained. One purpose of casing strings is to seal off loss intervals where high weight drilling mud cannot be sustained. In situations where this is not possible, the well must be plugged back and sidetracked from a shallower level.

There is always some uncertainty in the geology to be encountered as well as operational uncertainty while drilling such deep wells. In the planning phase, one often plans for back-up solutions or contingency solutions requiring different strategies to cope with unexpectedly difficult conditions. Figure 1-2 shows six alternative casing programs for the well of Figure 1-1.

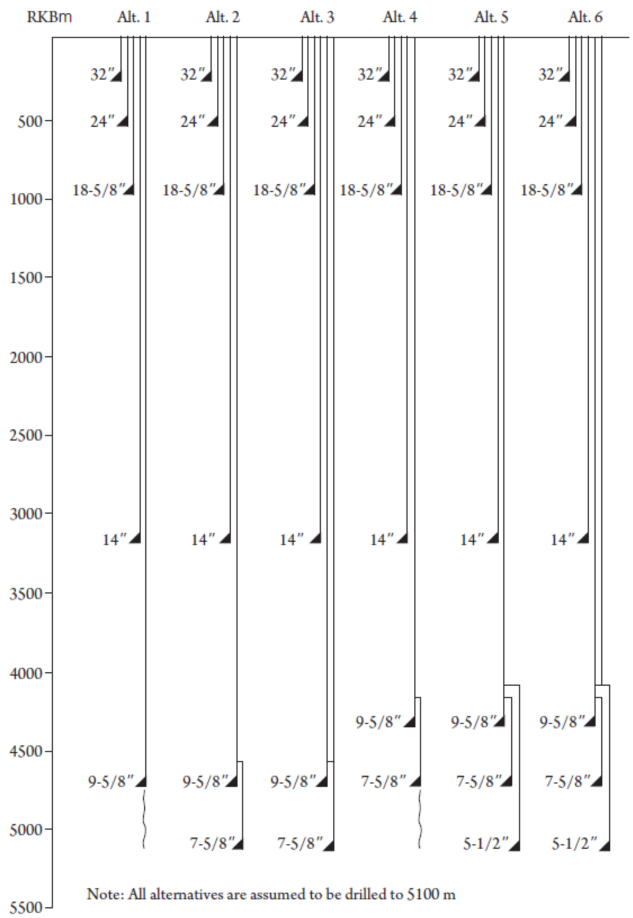


*Figure 1-2: Casing alternatives for an HPHT well (Aadnøy, 2010)*

A brief description of the casing setting depths is as follows:

- The 32-inch (813 mm) conductor casing has the main function of giving support to the wellhead and isolating the upper soft layers of the formations, generally sea floor muds and high porosity, uncemented sands.
- There are two surface casings, a 24-inch casing (610 mm) and an 18⅝-inch (473 mm) casing. The reason is a significant likelihood of encountering shallow gas in the 200-1000 m depth interval below the conductor casing.[4] The first casing seals these off in the shallowest part of the hole and permits drilling ahead with a higher weight drilling mud to control pressures in any thin gas seams in the 500-1000 m deep interval.
- The intermediate casing is set with the bottom of the casing string (the casing shoe) at 3200 meters depth. Here the lithology changes from clay-rich mudstones between 1000 and 3200 m (these often are associated with stability issues) to stronger chalks and limestones, and the temperature is becoming higher. At this stage, a specially formulated HPHT drilling fluid is introduced to handle elevated temperatures up to 180°C while sustaining adequate properties to clean the hole, control pressures, and circulate freely without gelation during trips (e.g., Taugbol *et al.* 2005).
- The 9⅝-inch production casing is set in the caprock above the reservoir. This is the most difficult operation during drilling, as too shallow a casing shoe placement gives a too weak wellbore, and too deep a casing point may lead to losses or blowouts.

Furthermore, the scenarios shown imply:

- Alternative 1. The well is drilled through the reservoir and logged. If the well is dry it is plugged.
- Alternative 2. If the logs show oil, a liner[5] is installed to prepare for a flow test.
- Alternative 3. The production casing was not designed for a flow test, so a smaller but stronger tie-back casing is installed
- Alternatives 4, 5 and 6. These are similar to alternatives 1, 2 and 3, except that if problems occur and the production casing is set too shallow, an extra 5-1/2-inch liner must be used to finish the well.

### 1.2.1 Time and Cost of a Deep Petroleum Well

Regarding the time it takes to drill such a deep well we will present some statistics in the Table 1-1 from wells drilled in the Norwegian North Sea area.

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[4] Shallow gas seams are endemic offshore and in most sedimentary basins and must be considered in planning. In crystalline rocks, metavolcanics, or low-grade metamorphosed sediments, gas outbursts are rare, small in volume, and are usually not specifically planned for. Caution dictates that it be on the list of elements to be aware of.

[5] A "liner" is a short casing string that does not extent to the surface. It is attached to the previous (higher and larger diameter) casing string with a sealing casing hanger.

Shallower wells might be drilled with an average penetration of 100 m/day, but at depth the drilling progress may be very slow and extra time is required to carry out geophysical logging, formation testing, coring, and setting the casing strings. This explains the low average drilling rates below. The wide span of times used for these five wells, from 111 to 256 days, is also explained by different drilling problems encountered during construction of these wells. These problems have to do with shale stability issues, encountering unexpected high-pressure zones that require higher mud weights and perhaps extra liners, lost circulation and gas invasion events that require time and careful circulation to fix, and other events.

*Table 1-1: Time and cost of some deep wells offshore Norway*

| **Well** | **Depth(m)** | **Time used(days)** | **Avg. (m/day)** | **Well Type** |
|---|---|---|---|---|
| 6506/11-7 | 4980 | 149 | 33.4 | Exploration well |
| 6506/11-8 | 4990 | 112 | 44.6 | Exploration well |
| 6506/11-9S | 5330 | 111 | 48 | Production well |
| 6506/11-A-1 H | 5962 | 256 | 23,3 | Production well |
| 6506/11-B-3 H | 5934 | 159 | 37.3 | Production well |
| **Average** | **5439** | **157** | **37.3** | |

The well studied is 5000 m deep. Assuming average construction of 37.3 m/ day the entire well will take 134 days to construct, or 4.5 months. Current cost of an offshore drilling operation is in the order of 4-5 MMNOK/day. The cost of the entire well is then 600 MMNOK or more. This estimate is on the low side. There are difficult wells drilled in Norway with nearly twice this cost.

## 1.3 Plugging and Abandonment of Deep Oil Wells

Dry or depleted oil wells are usually plugged and permanently abandoned. This is done with a long-term perspective, because offshore we can no longer access an abandoned well. The wellhead is removed, only leaving a cemented hole in the sea bottom. We will below give a review of the process of plugging and abandonment of oil wells in Norway.

The plugging and abandonment (P&A) of an oil well is regulated through the NORSOK D-010 Standard. This standard underlies all phases of drilling and well construction, and although developed in Norway, it is widely used worldwide as it has been adopted by many other offshore jurisdictions, and even by corporations themselves. Its most important principle is that in a well there shall always exist two independent barriers for blowouts. For example, during the drilling phase, one barrier is the hydrostatic pressure of the drilling mud which must be maintained higher than the pore pressure in the strata; the other barrier is the cased upper hole and the presence of a blow-out-preventer (BOP) stack on top of the casing to isolate deep pressures if these are encountered. There are also other measures taken such as careful drill mud monitoring, cuttings monitoring, drilling parameter monitoring, and so on, that help identify issues. We will briefly show the situation after a well is plugged and abandoned (Figure 1-3).

Figure 1-3 shows a P&A plan for an oil well. First, all casings which are not cemented are removed such that the plug makes direct contact with the rock formation or with a casing that is fully cemented into place. Then, the entire surface casing with wellhead is cut 5 meters below seabed. Finally, several cement plugs are set to satisfy the two-independent-barrier requirements set out in the regulatory guidelines. Mainly, the reservoir is isolated from the formations above, but often one or more extra plugs are set depending on the conditions encountered in the hole during drilling and evaluation. For example, there may be zones of elevated pressure higher in the wellbore that require an additional barrier to be set. Near-surface, the final cement plug is set. Quality checking (pressure performance of the seal, collection of cement samples) is performed throughout the sealing process, and the operations may even include using the drill string to give weight on top of the set cement plugs to test their strength and integrity.

| 9.8.3 Permanent abandonment - Open hole |
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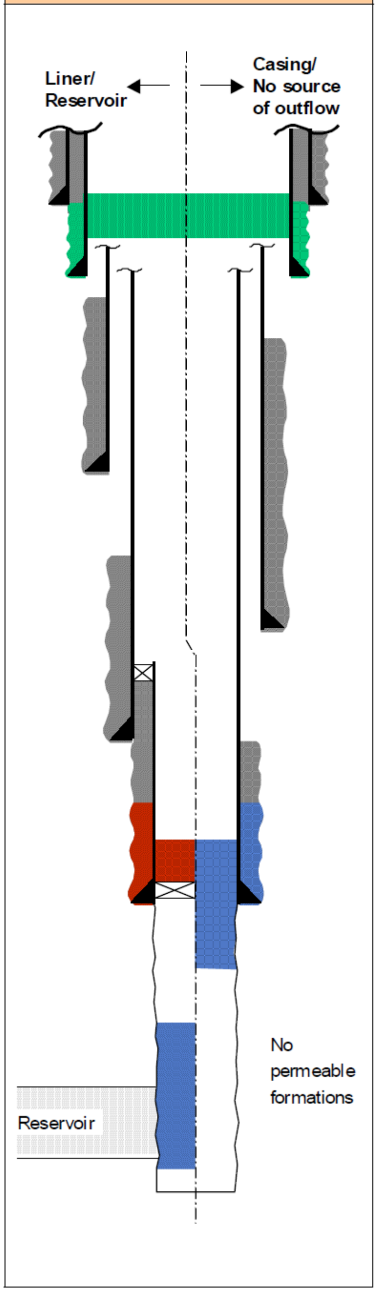


| Well barrier elements | See Table | Comments |
|---|---|---|
| **Primary well barrier** | | |
| 1. Cement plug | 24 | Open hole. |
| or, (“**primary well barrier, last open hole**”): | | |
| 1. Casing cement | 22 | |
| 2. Cement plug | 24 | Transition plug across casing shoe. |
| **Secondary well barrier, reservoir** | | |
| 1. Casing cement | 22 | |
| 2. Cement plug | 24 | Cased hole cement plug installed on top of a mechanical plug. |
| **Open hole to surface well barrier** | | |
| 1. Cement plug | 24 | Cased hole cement plug. |
| 2. Casing cement | 22 | Surface casing. |

Notes

a. Verification of primary well barrier in the “liner case” to be carried out as detailed in Table 22.

b. The well barrier in deepest casing shoe can for both cases be designed either way, if casing/liner cement is verified and O.K.

c. The secondary well barrier shall as a minimum be positioned at a depth where the estimated formation fracture pressure exceeds the contained pressure below the well barrier.

*Figure 1-3: Example of Plugging and Abandonment program for oil well (NORSOK D-010 Standard)*

*Table 1-2: Typical oil well plugging material (Khalifeh & Saasen, 2019)*

| Material | Examples |
|---|---|
| Cementing (setting) | Portland cement, pozzolanic cements, blast furnace slag-based cement, phosphate cements, geopolymers, hardening ceramics |
| In-situ formation | Shale, salt, claystone |
| Grouts (non-setting) | Unconsolidated sand or clay mixtures, bentonite pellets, barite plugs, calcium carbonate |
| Thermosetting polymers and composites | Resins, epoxy, polyester, vinylesters, including fiber reinforcements, urethane foams, phenol |
| Thermoplastic polymers and composites | Polyethylene, polypropylene, polyamide, Polytetrafluoroethylene (PTFE), Polyether Ether Ketone (PEEK), Polyphenylene Sulfide (PPS), Polyvinylidene Fluoride (PVDF), and polycarbonate, including fiber reinforcements |
| Metals | Steel, other alloys such as bismuth-based materials |
| Modified in-situ materials | Barrier materials made from in-situ casing and/or formation through thermal or chemical modification |
| Elastomeric polymers and composites | Natural rubber, neoprene, nitrile, Ethylene Propylene Diene Monomer (EPDM), Fluoroelastomer (FKM), Perfluoroelastomer (FFKM), silicone rubber, polyurethane, PUE and swelling rubbers, including fiber reinforcements |
| Gels | Polymer gels, polysaccharides, starches, silicate-based gels, clay-based gels, diesel/clay mixtures |
| Glass | |

Portland cement has been used for many years as the dominant plug material in the O&G industry; there are however some concerns. First, neat cement slurries generally shrink during setting, possibly giving rise to the potential for minor leaks through development of a behind-the-casing "microannulus", a narrow-aperture circumferential channel behind the casing, usually between the rock and the cement, that develops because of shrinkage. Second, are the cement quality and the placement quality good enough for long time exposure under the conditions of gas seepage, pressures and fluid chemistry in the subsurface? Concern about the long-term integrity of abandoned cased wellbores has increased in the period 2010-2020 because of increasing evidence of slow seepage of methane from depth under buoyancy forces (Dusseault and Jackson, 2014).

In more recent years, various groups and researchers have identified and studied plugging materials that could replace cement. Table 1-2 gives an overview. In particular, Type 2 in Table 1-2 is an interesting approach. Shales or claystones are often chemically reactive (montmorillonite or smectite clays); these react with low salinity water and swelling ensues. In addition, during drilling, stresses around the wellbore may change and lead to failure or collapse under the influence of the high in-situ stresses. Over time the wellbore wall itself may fail, swell, and establish a barrier, perhaps aided by steps taken during the abandonment process to encourage the yield and swelling processes. A great deal of knowledge exists in the O&G industry concerning the behaviour of shales, and this knowledge must be accessed and integrated with other information sources from the many studies conducted around the world on repository sealing.

A requirement for barriers is chemical and mechanical compatibility with the materials encountered (rock, fluids, casing) so that chemical degradation does not lead to the impairment of the barrier effect. Some of the barriers listed above, such as some rubbers, polymers and others may not qualify for long-term integrity, others may be indefinitely chemically inert under the conditions to be encountered at depth. There are several other granular-type barriers like quartz-packs and finely ground-barite packs used in the O&G industry. Both of these minerals possess low aqueous solubility and are quite unreactive geochemically; therefore, if such a barrier is properly placed as borehole backfill, it should last indefinitely, yet be removable if required. Finally, we note that mechanical bridging plugs and various types of inflatable (rubber or polymer) packers, some filled with cement, are widely used for various purposes in the O&G industry, and these technologies will likely be of value to the process of waste isolation and sealing.

## 1.4 Oil Well Reference to Deep Repository Well

The deep HPHT well outlined for the O&G industry offshore is a well-established technology. Nonetheless, we observe that the cost is high, and understand that there is a substantial technical and economic risk level to the oil company because of this, and risk mitigation measures are taken throughout the process of HPHT well planning and execution. Not all of thes measures are appropriate for a nuclear waste repository borehole in crystalline rock. We will now discuss which parts of this are relevant for design of a radioactive material repository borehole. In other words, how much of the oil well design framework is relevant to the placement of radioactive waste in deep boreholes?

An oil well is drilled to discover and exploit hydrocarbons, which are combustible. A considerable portion of the design is to always control the influx of (flammable) hydrocarbons into the wellbore by using casing strings and also a blow-out-preventer (BOP), which is a surface installed valve system to control unexpected pressures and fluid influx. A borehole drilled for repository purposes is not likely to need a pressure control system because among the criteria that would make a site suitable are the absence of hydrocarbons and the absence of fluid pressures in the surface that are higher than hydrostatic. However, there are often formation gases in sedimentary, metamorphic, and igneous rocks, so a low-pressure BOP might be considered, at least on the first pilot holes drilled during the early phases of the site qualification process.

Casings strings also serve the purpose of sealing off wellbore instability intervals arising from the presence of weak rock or high fluid pressures. Casings will still be needed in a repository borehole, but the number of casings, their depth and diameter, and even the materials from which they are made depends on the rock formations, in-situ conditions, and security level against leaks. In a very competent igneous rock, with an impermeable matrix, casing strings might be minimized, using only a surface casing to seal off any fluid access to shallow jointed rock features. Also, for a repository borehole, the casing placement might be designed in such a way that it can be removed before the well is plugged, either by drilling (polymer-based casing) or jacking. For example, if a steel casing is used for the 200 m long surface casing section, instead of being cemented into place, it is sealed against the rock with a packer system just above the shoe. When the borehole is being backfilled, the packer is released, and the steel casing section removed.

Most of the same geophysical logs encountered in the O&G industry will be run to define the geology of the site as precisely as possible. This is important for the design of the plugging material, for example to ensure it is chemically and radioactively compatible with the material being inserted into the well. The entire well should be as geochemically inert as possible for indefinite leak protection assurance. Here, in the geophysical logging domain, the O&G industry expertise will be critically important to achieve site and borehole qualification for the DBP repository.

Every time a casing is set in the O&G industry offshore, a pressure test, the LOT (casing shoe pressure Leak-Off-Test), is conducted. This not only defines the strength or the rock against fracturing and the integrity of the wellbore, but it also gives important information for stress modelling. One objective of site selection is to use an area of moderate lateral stress; that is, an area where the horizontal stresses are not so high as to lead to significant drilling issues. An in-situ stress analysis will be an important part of the risk assessment and qualification process for any repository site, but the O&G industry LOT approach also can lead to a small amount of opening of fractures in the rock mass near the borehole, so its use must be carefully evaluated. At this time, for stress measurements, we recommend over-coring techniques (e.g., Doe *et al*.

1981) from the mining industry[6] rather than the LOT approaches from the O&G industry to avoid subjecting the borehole to elevated pressures.

During drilling of an O&G well, unexpected drilling problems may arise; these are often associated with rock stresses and wellbore yield or fracturing leading to circulation losses. The latter is important as it cannot be detected with seismic surveys. The only way to fully qualify the integrity of an oil and gas well, or a repository borehole, is during and after the actual drilling process. Mud losses can be minor, or can be major, with pressures and perhaps fluids communicating via faults or intensely fractured zones over long distances. This is of course important for a repository borehole. At this time, we consider that part of the site selection and site qualification criteria will be the fluid flow integrity of the repository, and the presence of major mud loss zones would perhaps disqualify the site if these zones were deep seated. Later, we will show how a combination of mining and O&G industry technologies cab be highly useful in individual isolation borehole qualification for use for high-level waste placement.

During mining operations water is most commonly used as a drilling fluid because the rocks are strong and almost always chemically inert. For oil drilling, weighted drilling muds using clays and various chemicals are used to maintain pressure and chemical stability. These particulate substances also seal off the formation during leaks because the small particles of clay and barium sulphate ($BaSO_4$) enter a short distance into the thin aperture cracks and pores; often, additional chemicals such as soluble polymers are added to the drilling fluids to enhance the sealing effect. The oil industry has a large competence in building fluids to stop leaks. It is foreseen that this competence will be used when designing drilling muds but also when designing plugging materials. One strategy used will be to design for redundancy. Perhaps O&G technology can be used to help seal off shallower zones that could serve as fluid pathways.

Some of the plugging materials used for oil wells might apply favourably to radioactive waste isolation in deep boreholes if these materials qualify for long-term stability criteria.

## 1.5 Shallower Onshore Oil Well as a Reference

Typically, this onshore well will be similar to the deep well, only shallower. A 2000 m deep vertical well offshore Norway would take 40 days at a cost of 200 MMNOK. A 2000 m deep well onshore in Alberta, Canada (for example), may cost as little as 10 MMNOK. At this stage, we will leave details out but may refer to both the shallow well (e.g., for coiled tubing technology) and the deep well (e.g., wireline systems) for processes and procedures.

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[6] Over-coring is used in dense elastic rock to estimate stresses in the ground. The method involves placement of high-precision strain gauges in a small pilot hole, then, using a thin diamond bit, advancing a large diameter outside annulus (the overcoring process), and measuring the resultant strain. Using elastic theory, the strain results are analyzed in terms of stress change. The overcored section with the strain devices is brought back to the laboratory, and further tests may be done on the system and the overcored section to assure good quality stress estimates.

## 1.6 Multiple Downhole Branches

A deep repository borehole 5000 m deep in a sedimentary sequence can be costly, as discussed above, particularly if a complex subsurface involving pressurized pore fluids and weak rocks is encountered. This complexity would lead to the need for a number of security casings, and a reduced repository borehole diameter at depth, providing limited volume of storage for the radioactive materials. Instead of drilling several vertical boreholes from surface, multiple branches can be drilled from a mother-bore (Figure 1-4). This is a solution much used in the O&G industry, and the advent of horizontal drilling technology has changed approaches to resource development offshore and onshore. Note that in a multiple-branched borehole case, the branches are located at depth, and the upper part of the borehole is the only access path. This carries risks if there is an impairment of the unique path, but it also carries advantages as only one man-made "pathway to surface" has to be sealed and backfilled, and shallow laterals can be used to demonstrate the isolation of a deeper lateral by hydraulic or seismic testing.

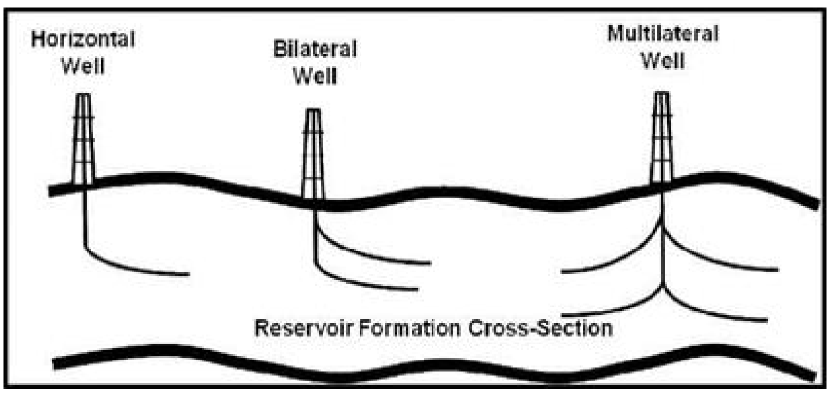


*Figure 1-4: Common well trajectory solutions for oil and gas wells.*

Several commonly used solutions for complex trajectory and multiple branch O&G wells are shown in Figure 1-4. There is a considerable amount of technology developed for these solutions. Because these are developed for O&G reservoirs, they are designed for pressured conditions, the potential presence of large volumes of gas, and various completions solutions are implemented, including accessibility needs for later workovers and well interventions. There are also many surveillance technologies developed in the O&G industry including downhole temperature and pressure measurements, signal transmission systems such as electrical pulsing and fibreoptic transmissions, and fibreoptic and tiltmeter displacement measurement devices.

For applications to radioactive waste repository development, the borehole construction technologies are most important but also the various measurement and surveillance technologies used for data gathering and quality assurance and control (QA/QC). Most likely, in any waste placement scenario using multiple deviated boreholes from a central mother-bore, a well-understood technology, we will start at bottom, deposit some radioactive waste, set a plug, and sidetrack to generate a lateral branch above. In this way, many branches can be established, working from the bottom upward. Alternatively, a horizontal multi-lateral borehole approach could be envisioned (Brunskill, 2006). Consideration of these variations will be part of the next phase of consideration for this repository project.

## 1.7 Summary

Using deep boreholes for radioactive waste placement has a high potential to minimize risks of long-term contamination events associated with radionuclide escape. O&G well technologies can in part be used to assess the repository site, construct these boreholes efficiently, evaluate them in great deal, and thereby minimize risk. These technologies can be brought to bear during development and placement of wastes, buffer material, sealants and backfill. More specifically:

- Oil well technology is well proven and commercially available. Depending on the solution chosen, vertical single boreholes or deviated multiple branch boreholes, most tools and equipment should be considered as “off-the-shelf” technologies.
- Geomechanics analysis is a highly important issue for O&G well drilling, and these analysis methods can be advantageously used in a radioactive waste repository design based on the deep borehole concept. In-situ stress estimation and time-based tectonic effects are also all-important issues for oil well drilling.
- A large part of the geological risk for future leaks from a repository will be evaluated during drilling through pressure/flow testing and well log analysis, and these methodologies are highly advanced in the O&G industries.
- Repository boreholes need a tailored detailed design as they are not aimed at high-pressure oil reservoir development but will deal with normally-pressurized rocks with joints containing water. Well control, however, may still be required due to the possible (but unlikely) presence of small amounts of gas.
- O&G drilling mostly takes place in sedimentary rocks, occasionally in very low-grade metamorphic rocks, and in some sedimentary basins, igneous rock layers (e.g., lava flows) exist that have to be penetrated to access deeper oil and natural gas deposits. Repository boreholes are more likely to be drilled in crystalline rocks (granites, gneiss...) than sedimentary rocks. Boreholes must be tailored to the type of rocks and to the repository design goals. In particular, this relates to wellbore stability, which in turn depends on in-situ stresses, rock strength, intensity of natural fracturing, and other factors and rock properties that can only be finally delineated during the site qualification phase.
- Borehole quality, fluid behaviour, data for strength and stress modelling, and many other sources of information can be obtained from the drilling experience and from the logs developed during drilling (cuttings logs, drilling logs, mud logs, geophysical logs…).
- The O&G industry has extensive software systems for the building of digital geological and geological engineering models and integrating highly detailed information in 3D maps.

- The O&G industry has a highly sophisticated array of down-hole tools that can be lowered, installed, and raised on wireline hoist units. This includes all of the geophysical logging tools mentioned, borehole televiewers, specialty systems and many means of installing bridge plugs, packers and other materials that may be of interest in a Deep Borehole Placement (DBP) repository context.
- Multi-branch wells, vertical, inclined or horizontal in attitude, are common in the offshore O&G industry, and this technology can be brought to the design of a DBP repository if it is considered appropriate (i.e., a single upper borehole to seal for several deep branches).
- The O&G industry has developed the coiled tubing system for treating O&G wellbores ("workovers"). This expertise is highly advanced, "off-the-shelf", and should prove to be ideal for a number of operations associated with the waste emplacement phase of the DBP repository.
- Some plug and abandonment materials and procedures developed for oil wells may qualify for long-time DBP repository boreholes.

In summary, there is a great depth of knowledge and capabilities residing in the world and the Norwegian O&G industry, and major aspects of this expertise and technical skills will be brought to bear on the site and borehole qualification[7], development and waste placement phases of the DBP repository project.

[7] We deliberately use the term "qualification" to indicate that the repository (or borehole, or other system) has passed a set of standards and therefore "qualifies" and may proceed to the next stage in the process. We prefer "qualification" to other terms that may not clearly imply that there are specific performance standards that must be met at each "qualification" point in order to move to the next stage.

# Chapter 2: Land Wells and Boreholes in Crystalline Rock

## 2.1 Overview of Wells and Boreholes in Crystalline Rock

Onshore wells and boreholes in igneous and crystalline rock, particularly deep wells, are significantly less common than wells in sedimentary rocks (O&G wells). However, partly because of the emergence of geothermal resources as a potentially viable green energy source, recent decades have seen the emergence of a substantial body of literature and technological development in deep hard rock drilling in pressurized and hot systems. In addition to geothermal exploitation applications, scientific investigations, mineral exploration, $CO_2$ sequestration (in ophiolites), and mining operations all have generated support for development of improved drilling practices in stiff, strong rocks.

At present, the International Continental Scientific Drilling Program (ICDP)[8] funds programs and provides technical and financial support for projects for advancement of deep boreholes related to programs expanding the scientific understanding of the shallow crust, including heat flux and the nature of the geothermal resource at depth. The desire to drill deeper to refine geological and geophysical models of the shallow crust has helped encourage the development of drilling technology for igneous and crystalline rocks. In addition, the direct exploration and exploitation of geothermal sources through wells has also been a force driving the development of improved technologies as nations seek forms of fossil-fuel-free energy that have lower impacts on climate change.

However, the academic literature addresses these activities somewhat sparsely, as these developments are technical in nature and becoming more and more privately funded as they move from the academic/research environment into the commercial/services environment. These corporations focus on developing and implementing proprietary technology; therefore, they protect their tradecraft and experiential base, and provide limited public information of a detailed nature. However, joint venture research and development programs such as ThermoDrill[9], NEXT-Drill[10], and INNO-Drill[11] between academic institutions and private companies have resulted in improvements in different areas of drilling and the development of novel technologies with results available in the scientific literature. Finally, we note that evaluation of drilling and borehole operations techniques will require a different investigation approach than an academic review of the literature; this will require direct engagement with

[8] https://www.icdp-online.org/home/

[9] http://www.thermodrill-h2020.org/

[10] https://www.sintef.no/en/projects/next-drill-numerical-experimental-technology-platf/

[11] https://www.sintef.no/en/projects/inno-drill-technology-platform-for-research-based-/

appropriately experienced, technology-qualified corporations so that performance, product quality, methodologies and costs are quantified.

This chapter will overview several different drilling projects to outline the potential for advancing the understanding of drilling deep boreholes in crystalline rock. Although there may be interesting emerging technologies, such as electromagnetic discharge drilling (Oglesby, 2014), plasma drilling, explosive drilling and other developments, at the present time air hammer and water hammer percussion drilling are the most likely candidates for the DBP repository concept scenarios. Air hammer and water hammer percussive drilling is widely used in the mining industry worldwide for large diameter boreholes (40-80 cm) in crystalline rocks; i.e., they are technically proven with known costs. Nevertheless, the knowledge developed in scientific and other drilling programs will be useful to developing and understanding the requirements for construction of a DBP repository, so an overview of deep drilling programs around the world is provided. In addition, general discussion is undertaken about different issues related to drilling in igneous/crystalline rock and the applicability to the DBP repository concept. We also presume that the issues arising in igneous and metamorphic rocks are similar to the issues in stiff, brittle, low-porosity sedimentary rocks, as in both cases we are dealing with high-strength materials, low-permeability materials, and flow systems dominated by the natural fractures that are invariably found in such rock masses.

Here, based on an extensive literature assessment, we immediately highlight the most dominant issue for long-term DBP repository security:

- **Fluid flow carrying dissolved radionuclides is by far the dominant pathway of concern for any escape from a deep DBP repository.**
- **Not considering the DPB borehole itself, fluid flow in highly competent, low-porosity igneous, metamorphic and sedimentary rock masses will take place dominantly (likely exclusively) through natural fractures.**
- **Understanding and quantifying the natural fracture systems from many points of view (hydrological, structural, geomechanical, geochemical…) will be the most important technical/scientific task in qualifying and constructing a DBP repository**.

## 2.2 Scientific Exploration Boreholes

To develop a deeper understanding of the geological processes deep below the earth's continents, scientific drilling programs starting in the 1970s set out to drill into the earth's crust beneath the continents to significant depths in order to collect information.[12] To construct these

[12] These on-land projects are different from those addressed in the famous and ongoing IODP – International Ocean Drilling Program – which focuses on oceanic crust and off-shore sedimentary basin drilling: http://www-odp.tamu.edu/. Although such drilling is into igneous rock, it is basaltic and not granitic and thus of very different

scientific exploration boreholes, specialized drilling technology built upon existing deep O&G well technology is typically used. These deep exploration boreholes have led to significant increases in understanding of deep crustal geology, geochemistry, and geomechanics, along with understanding the requirements to construct the deep boreholes that allow access to these rocks. The experiences gained during drilling, sampling, and downhole testing from scientific exploration boreholes will help guide any programs associated with the DBP concept.

This section will summarize several major scientific exploration boreholes, focusing mainly on their drilling and construction requirements. The boreholes selected were either drilled completely in crystalline rock, had some amount of sedimentary rock overburden or were deviated into sedimentary units deliberately. For some projects, multiple boreholes were drilled; i.e., the first hole being a pilot hole to characterize the geology before a main hole was advanced. Note that this pilot hole approach is likely to be part of a DBP project, particularly in the initial phases when rock mass information is needed for site qualification and for construction of a detained three-dimensional geological engineering model. A pilot hole is different from a guide hole; the former is to outline the subsurface in detail, the latter is deliberately drilled in a chosen trajectory to be reamed out later to the final diameter. This pilot hole and guide hole approach allows for use of standard size geophysical logging tools and well-testing systems (e.g., double-packer hydraulic conductivity testing) that do not exist for large-diameter holes (50-60 cm). In other words, each large-diameter waste placement borehole will also be qualified[13] individually through detailed guide hole investigation, in addition to the characterization and testing of the pilot holes that were used in general site qualification procedure.

The exploratory boreholes summarized below all have a termination depth deeper than 4 km. The only hole that explored the use of percussive techniques for part of the project was the most recent one, the Chinese Continental Scientific Drilling project.

### 2.2.1 Kola Superdeep Borehole

The Kola Superdeep Borehole project in northwest Russia (then the Soviet Union) on the Kola Peninsula was a geological exploration and technology project beginning in 1970, with drilling ending in 1989. Technical and scientific information is summarized in books about the project

properties from typical crystalline rocks onshore, and has not been subjected to deep burial, prolonged erosion and uplift, and sudden stress relief following deglaciation.

[13] We re-emphasize again that the term is chosen deliberately to avoid any implications that only characterization is needed: specific “qualification” thresholds and criteria will be defined and met before proceeding to the next stage. Although the thresholds and criteria will be varied and somewhat flexible in practice, they nonetheless are standards to be met.

(Kozlovsky, 1987; Fuchs *et al*., 1990). The Wikipedia website provides a brief summary of the timing and achievements.[14] The project features are summarized in the following paragraph.

The project drilled a deep hole with a series of smaller diameter cemented casings to achieve and advance a 21.6 cm final diameter borehole to a depth of 12.2 km in shield rock in the Kola Peninsula in northwest Russia in the Baltic Shield igneous craton. The Baltic Shield is an ancient continental crust craton at least 900 million years in age, and it has particular relevance to the development of a DBP repository in Norway, as the Baltic Shield extends to the igneous rock margins of western Scandinavia, the Sveconorwegian sector. These include the exposed igneous and metamorphic rocks in southwest Norway, the deep basement rocks under the younger rocks of the Caledonian Nappes in central and northern Norway, and the basement rocks under the sediments that are found on the continental shelf offshore Norway, near the shoreline (Bingen *et al.,* 2005; Bingen and Solli, 2009).

At the Kola site, Baltic Shield crystalline basement was near surface. Approximately 3592 m of core was collected from the borehole using a wireline core barrel recovery technique. Additionally, geochemical samples of the fluids encountered showed meteoric[15] water at depths of up to 800 m, a transition zone down to 4 km depth, and metamorphogenic waters at greater depths. At depths exceeding 10,000 m, natural fractures were still encountered with mobile water in the fractures, an unexpected finding, although it was shown geochemically that the deep waters were unable to communicate with the waters in the upper four kilometres that had surface (meteoric) water characteristics. In addition, free hydrogen was encountered at great depth during drilling. This project still holds the record for deepest borehole drilled in crystalline rock, and the greatest vertical depth for any borehole.

### 2.2.2 KTB

The KTB deep continental drilling programs in SE Germany ran from 1987 to 1994. The technical details of the project are summarized by Bram *et al*. (1995) and Haak and Jones (1997). A summary is provided below, a more extensive summary can be found in Wikipedia.[16]

The project consisted of two phases. The first phase was completed in 560 days to reach a depth of 4 km with a 16.5 cm final diameter borehole, while collecting approximately 3564 m of core. This pilot hole was then reamed to a larger diameter during the second phase, which involved drilling using a specifically designed drill rig to drill to a depth of approximately 13,500 m. A diameter of 37.5 cm was sustained for the first 5 km depth. The final depth of 9.1 km was

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[14] Kola Superdeep Borehole: https://en.wikipedia.org/wiki/Kola_Superdeep_Borehole

[15] We may define "meteoric" waters as groundwater that has been recharged, at least in part, since the beginning of the Pliestocene Epoch glaciation, and thus is circulating (albeit perhaps extremely slowly) within an active flow system experiencing recharge and discharge.

[16] KTB Borehole: https://en.wikipedia.org/wiki/German_Continental_Deep_Drilling_Programme

achieved with a 16.5 cm diameter bore. The borehole was halted due to well stability issues and failure of the electronic steering system in the high temperature environment (an unexpectedly high geothermal gradient was encountered at depth). The drilling was completed with 40 m long drill pipe stands (4 × 10 m long joints per stand) with a custom designed 83 m tall rig. These dimensions are common in offshore drilling platforms and ships. Figure 2-1 shows the final borehole and casing dimensions upon completion.


*Figure 2-1: KTB Main Borehole Dimensions and Casing Scheme (Bram et al., 1995)*

### 2.2.3 San Andreas Fault Zone Observatory at Depth (SAFOD)

The San Andreas Fault Zone Observatory at Depth (SAFOD) was a scientific drilling program conducted between 2002 and 2007 to examine the rock mass adjacent to the San Andreas Fault in California, USA. The project involved advancing two boreholes, one vertical pilot and one deviated borehole. The project is outlined by Harms *et al*. (2007) and Zoback *et al*. (2010). A summary of the project is provided below. Wikipedia provides a somewhat more extensive summary of the main aspects of the program, and additional references.[17]

The pilot hole involved drilling a 17.8 cm cased outer diameter vertical hole to 2.2 km depth. The pilot hole allowed for the collection of preliminary data and geological information to aid in the main borehole advancement. The main borehole consisted of a deviated borehole with a length of 4 km. The main borehole was deviated at 1.5 km to 60° across the San Andreas fault. The entirety of the boreholes was not drilled in crystalline rock, as sedimentary rock overlies the crustal rock to a depth of 750 m below ground surface. Additionally, a brief portion of the deviated borehole advanced through an unknown sandstone unit. The borehole was constructed with a final diameter of 21.6 cm. Instrumentation was installed down hole in the faulted region, but only worked for a few weeks before encountering severe technical difficulties. Figure 2-2 shows the geological profile the pilot and deviated hole advanced through.

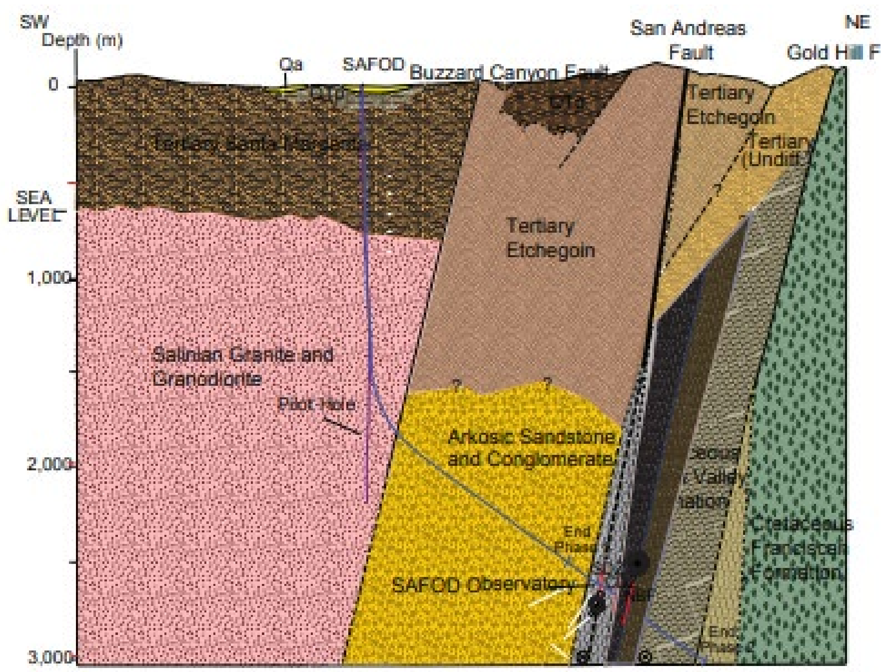


*Figure 2-2: Cross-section of SAFOD geology and bore paths for pilot and main boreholes (Zoback et al., 2010)*

[17] SAFOD Borehole: https://en.wikipedia.org/wiki/San_Andreas_Fault_Observatory_at_Depth

### 2.2.4 Chinese Continental Scientific Drilling (CCSD)

The Chinese Continental Scientific Drilling (CCSD) was a scientific drilling and technological development project aimed at exploring high-pressure crustal rocks in central China. Wang *et al.* (2015) authored a book about the drilling engineering, design, and results for the CCSD program. A summary of the drilling is provided below, and several related papers may be found in a special issue of Tectonophysics, edited by Ji & Wu (2009).

A pilot borehole was advanced to a depth of ≈2 km with a diameter of 75 mm to examine to geological conditions. Initially, the program was to be a two-hole program but due to the limited deviation in the pilot hole, it was decided that the main hole would be drilled from the pilot hole. The main borehole was drilled to 5158 m to explore the ultra-high-pressure metamorphic rocks that characterize the region's crust. The borehole was completely cored with a final diameter of 154 mm. The borehole's upper 3.4 km were later reamed to increase the diameter with multiple passes. The hole was cemented and cased to a depth of 4800 m with the bottom of the bore uncased. Figure 2-3 shows the final constructed dimensions and casing scheme.

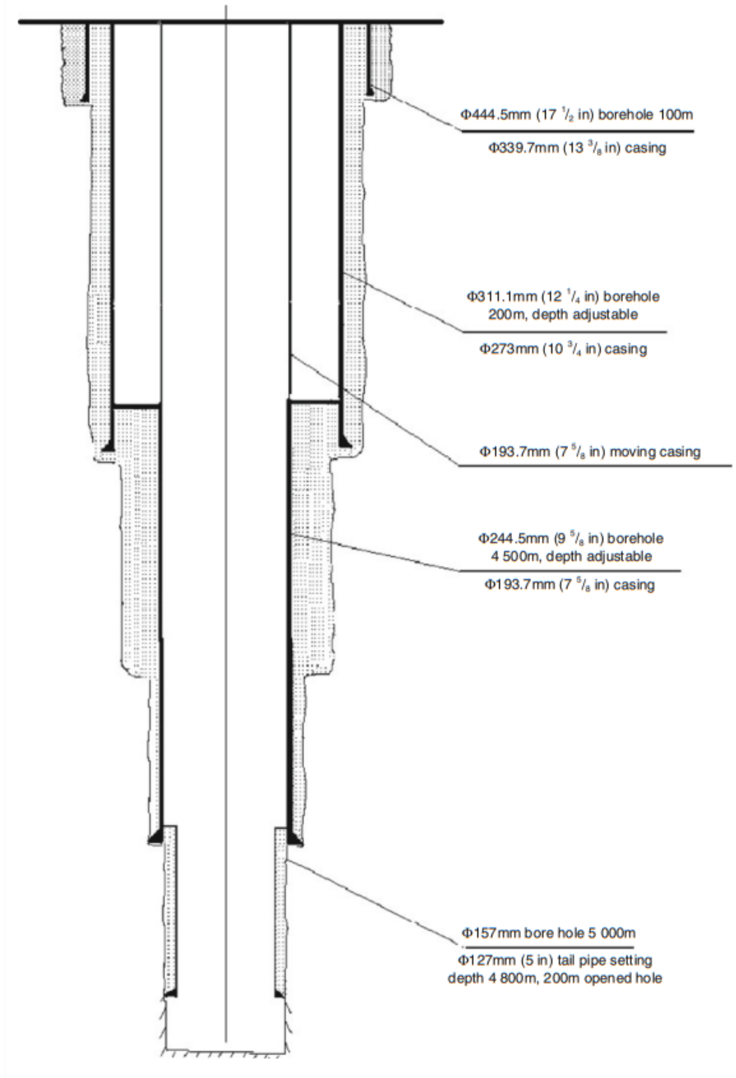


*Figure 2-3: CCSD final borehole dimensions and casing scheme (Wang et al., 2015)*

In addition to the drilling program, a technology development and evaluation project ran concurrently. The program resulted in the assessment of different drilling technologies and techniques for drilling a borehole into deep crystalline rock. Technologies evaluated included: drill bits for coring, reaming, and non-coring, drilling as well as technologies for verticality control and drilling fluid composition. A coupled economic and technical analysis was completed to evaluate the best coring technique. It was determined that a specifically developed positive displacement motor hydrohammer lifted using the drill sting resulted in the most cost-effective means of retrieving high quality core samples.

## 2.3 Geothermal Wells

Geothermal energy has become an increasingly attractive alternative energy source achieved through tapping into the high temperatures rock masses deep in the earth's crust. The future of geothermal energy involves four different approaches to the development of the earth's heat:

- High Grade Geothermal Energy involving direct dry or wet steam for power.
- SedHeat, or Sedimentary Basin Geothermal Fluids, warm to hot (50-150°C) liquids in deep porous permeable rocks that can be extracted commercially for heat, power, or both.
- Enhanced Geothermal Systems (EGS), involving warm to hot (50-250°C) igneous and dense low-permeability sedimentary rocks at considerable depth, usually greater than two km.
- Shallow Geothermal Systems that involve heat-pump based geothermal heat extraction and possible heat geostorage to depths of a kilometer or less.

Of particular interest to DBP repository concepts is that the energy is extracted through wellbores, particularly in EGS approaches because these are the most likely to involve stiff, brittle crystalline or sedimentary rocks of low porosity. To date, probably 95% of the geothermal wells drilled worldwide were for High-Grade Geothermal Energy or for SedHeat, but interest is increasing in EGS. A large geothermal project would involve an array of wells drilled into the hot region, and particularly if the project is a major steam production project, large diameter wellbores are needed to provide sufficient flow rates without excessive energy losses. Wells in high-grade geothermal sites are usually drilled in exceptionally hostile environments with high temperatures, high fluid pressures, and high concentrations of carbon dioxide and sulfurous gases. These conditions result in significantly more challenging conditions than wells drilled for oil and gas extraction, and do not reflect the conditions expected in any DBP repository application. Geothermal EGS wells are also typically larger in diameter than standard oil and gas wells to reduce wellbore friction losses at the high fluid flow rates needed.

Chapters 5 and 6 in the Massachusetts Institute of Technology monograph on geothermal energy (MIT 2008) contain useful information related to drilling and assessing EGS systems at depth. Although not all of the information is directly relevant to the DBP concept, valuable information can be gleaned from the comprehensive discussions.

Knowledge from early EGS projects in this emerging energy sector is useful for DBP repository assessments. Several important projects are briefly described here.

### 2.3.1 EGS Projects in Finland

Two projects in Finland involve EGS wells drilled in the Helsinki region for district heating. One is the Vantaa project[18], the other the Espoo project[19], roughly located on Figure 2-4.


*Figure 2-4: Locations of EGS drilling near Helsinki (Courtesy: Google Maps)*

*Figure 2-5: Rig Drilling a 6.5 km deep hole in Espoo Finland, 2019 (Courtesy: Numa Hammers)*

The Espoo project is of particular interest for several reasons, the most important one being that the 6.5 km deep borehole was advanced using percussive methods and the world's largest drilling rig designed for EGS applications in stiff, brittle crystalline rocks (Figure 2-5). The hammer drilling

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[18] https://www.vantaanenergia.fi/vantaan-energia-rakentaa-geotermisen-maalampolaitoksen/

[19] https://www.st1.com/geothermal-heat

achieved maximum penetration rates of 10-25 m/hr, approximately 5× to 10× the rate of conventional rotary drilling in crystalline rocks.[20] The borehole was deliberately kept vertical, and deviated borehole drilling was not utilized in this case.

### 2.3.2 Soultz-sous-Forêts

Soultz-sous-Forêts was a geothermal project in France starting in 1987, with drilling ending in 2004. The project was conducted as a scientific demonstration project to develop an enhanced geothermal reservoir in "hot dry" rocks. The project is summarized by Gérard *et al*. (2006) and Genter *et al*. (2010), and a summary PowerPoint presentation is available.[21] This project, over its life span, involved many researchers and graduate students, with over 800 publications of various types generated. A summary of the project is provided below.

The project evolved in phases, ultimately culminating in the construction of four wells and one exploratory borehole with three of the wells been greater than 5 km in depth. The diameter at the borehole terminus was approximately 25 cm for the fluid extraction wells. By the last set of boreholes, the construction was taking between 5 to 8 months per well. The entirety of the boreholes was not drilled in crystalline rock, as overburden and sedimentary rocks were encountered to a depth of 1.4 km. Standard oilfield rotary drilling and coring methods were used. All but the first borehole were slightly deviated, originating from a single surface drilling pad, with a bottom-hole spacing of 600 to 650 m at hole termination. Figure 2-6 shows the profiles of the boreholes.[22]

### 2.3.3 Basel-1

The Deep Heat Mining Project in Switzerland was undertaken to create an enhanced geothermal system near Basel, Switzerland. Haring *et al.* (2008) summarize the preliminary technical findings, but large numbers of scientific and engineering articles, student theses, and economic models have been published as a result of this project. A summary of the drilling program is provided in the following paragraph.

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[20] These data are found on the Numa Hammers website: https://www.numahammers.com/

[21] PowerPoint high-level look at the Soultz-sous-forêts geothermal EGS project by Geo-Elec: http://www.geoelec.eu/wp-content/uploads/2013/07/GEOELEC_Soultz_Pise.pdf

[22] Deepening a hole at Soultz-sous-forêts is described in a PowerPoint presentation at: https://www.researchgate.net/profile/Dimitra_Teza/publication/266485076_Drilling_of_Hot_and_Fractured_Granite_at_Soultz-sous-Forets/links/5857b7fb08ae544d8863bf00/Drilling-of-Hot-and-Fractured-Granite-at-Soultz-sous-Forets.pdf

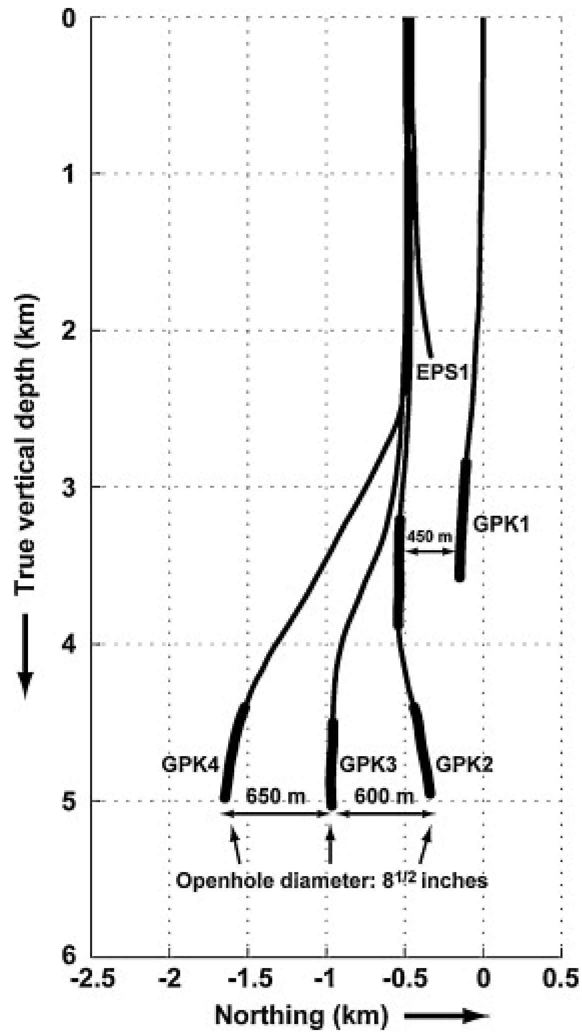



*Figure 2-6: Profile of borehole advanced for Soutlz-sous-Forêts Project (Genter et al., 2010)*

The Basel-1 borehole was drilled to a depth of 5 km through 2.4 km of sedimentary rock and 2.6 km of granitic basement. Drilling operations ran from May to October 2006. The ultimate diameter at the borehole at total depth was approximately 21.6 cm. The borehole was first drilled to 4.6 km at 25.1 cm in diameter prior to completing the final phase of drilling to open the hole to 5 km. The project was cancelled when hydraulic stimulation of the reservoir triggered microseismic events greater than magnitude 3.0. Figure 2-7 shows a cross-section of the boreholes, the lithology traversed, and the casing scheme utilized.

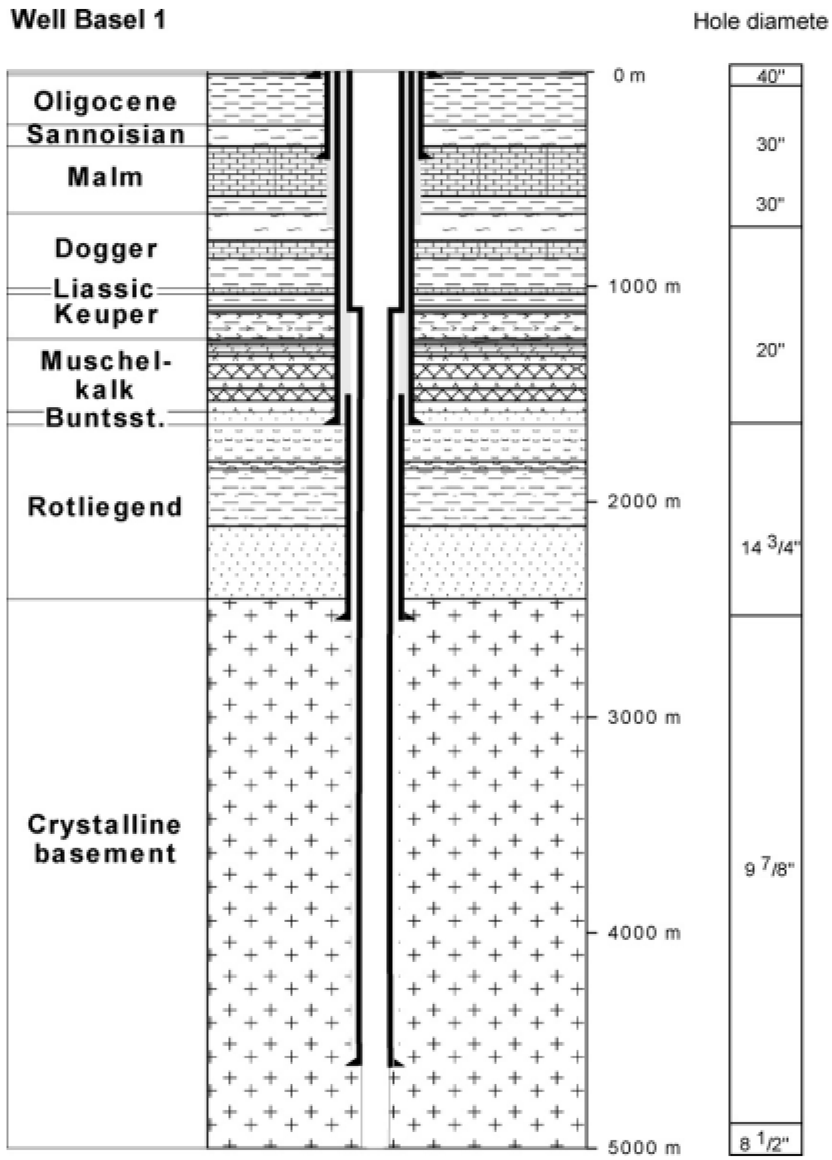



*Figure 2-7: Basel-1 geology and borehole cross-section with casing scheme (Haring et al., 2008)*

### 2.3.4 Icelandic Deep Drilling Program (IDDP)

The Icelandic Deep Drilling Program (IDDP) involved exploration of geothermal resources in southwest Iceland. The project began in 2000 with the IDDP-1 well drilled beginning in 2008-2009. A second well (IDDP-2) was drilled in 2016 and 2017 after complications arose with IDDP-1. The project is summarized in proceedings by Weisenberger *et al.* (2019).

IDDP-1 was drilled to a depth of 2104 m before it encountered a magma chamber resulting in temperatures exceeding 900ºC. Drilling of IDDP-2 was completed in 168 days to a depth of 4650 m from a starting point of 2507 m using an existing well in the Reykjanes production fields. The well was deviated at 2750 m with a final diameter of 21.6 cm at depth. Drilling was completed with a Bentec 350 electric top drive drill rig using a tricone bit, a conventional approach to rotary drilling.

## 2.4 Comparison of Oilfield and Mining Drilling

In summary, it is possible to drill deep into crystalline rocks that are stiff and brittle using currently existing drilling methods acquired from the O&G industry. A limitation of most of the deep drilling projects in the world for potential application to a deep borehole waste isolation project in stiff, brittle rocks is that only oilfield rotary techniques have been used in order to obtain core and to control downhole pressures. The techniques developed for controlled drilling into deep rock masses developed by the oil industry are intended to solve a number of issues (see Chapter 1) that are not likely to arise in the drilling of boreholes for a moderate depth repository. These issues include coping with high pressures, strongly flowing water, the presence of oil and gas, complex well trajectories (especially offshore), high temperatures, and borehole instability in weak sediments which gives rise to the need for weighted drilling fluids of special chemistry to enhance stability and control pressure.

The oil industry developed standard oilfield drilling practices that use down-hole "mud motors"; i.e., moving-cavity positive displacement drilling motors actuated by the circulating drilling fluid. Mud motors allow much easier directional and horizontal drilling than other drilling techniques, and have displaced conventional rotary table drilling in most offshore and horizontal well drilling.

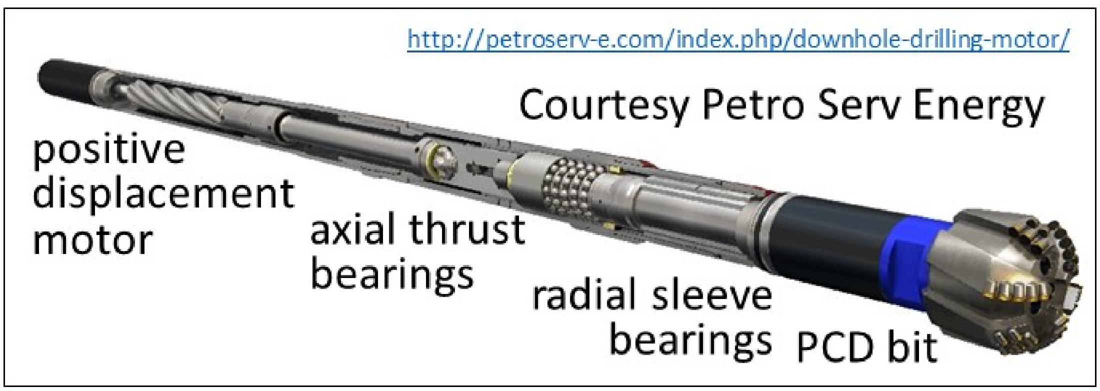



*Figure-2-8: Petroleum industry downhole drilling motor assembly (Courtesy: Petro Serv Energy)*

Figure 2-8 shows a typical downhole assembly for oilfield drilling, with robust bearings to take high loads, a positive displacement (progressive cavity) motor, and in the image, a polycrystalline diamond insert bit.

Widespread use of percussive methods in deeper oilfield drilling (Han *et al*., 2006) has been carefully researched and simulated (Bruno, 2006). It has not been adopted quickly because of pressure control needs, because of continued advances in downhole mud motors and better drill bits (Regener *et al*., 2005) for more conventional rotary drilling, and because of the heterogeneity of the rocks encountered in the oil and gas development industry, compared to crystalline rock drilling. Nevertheless, for drilling in strong, brittle rocks, air percussion drilling is being more commonly adopted (Pletcher *et al*., 2010). The advent of the shale gas and shale oil industry in the period 2005 – 2015 in the United States has led to much greater interest in percussive drilling because the typical sedimentary rock masses (Paleozoic strata) penetrated to access these resources are far more brittle and stiffer than most of the sedimentary rocks associated with conventional oil and gas development.

## 2.5 Mining Industry Drilling in Crystalline Rock

Drilling of deep boreholes, shafts, and access openings over a wide range in sizes in crystalline rock is widely recorded in the mining engineering literature for various exploratory and development activities. These boreholes and drilling methods developed in the mining industry are, however, considerably less understood and studied openly than oil well drilling approaches, are often less well documented in the literature, and in some applications have dimensions that vary significantly from the presumptive design dimensions of the DBP repository concept (e.g., narrow-hole diamond drilling). Nevertheless, the mining industry will almost certainly be the source of the drilling technology for a large-diameter, deep borehole waste placement facility in strong, brittle crystalline or low-porosity sedimentary rocks.

In the mineral exploration industry, slim diameter exploratory holes are advanced to gather core samples to log the lithology and determine the grade and extent of an ore body. These ore bodies are commonly found in crystalline (igneous and metamorphic) rocks or in dense sedimentary rocks (e.g., strata-bound Mississippi valley-type lead-zinc ores), requiring drilling bits suitable for cutting through strong and abrasive host rock. The diameter of these types of exploratory boreholes is usually BQ to HQ in size (approximately 6 to 9.6 cm outer diameter) and bits, drill strings and rigs are widely commercially available. Larger diameter sizes capable of obtaining cores of 100 mm and higher are also available for rock mechanics sampling needs.

Diamond core drilling is generally the most popular method for exploration as it allows for collection of intact representative samples over long borehole lengths using wireline core retrieval through the drill pipe. Boreholes advanced for mineral exploration extend to depths of greater than 4 km (Fletcher, 1992). Diamond drilling with continuous coring will almost certainly be the preferred exploration drilling technology for the DBP concept. This will be addressed in a later chapter in much detail because of the need for careful rock mass evaluation, perhaps for every DBP placement hole.

Figure 2-9 shows a typical diamond drill exploration drilling rig and a schematic view of the coring process.

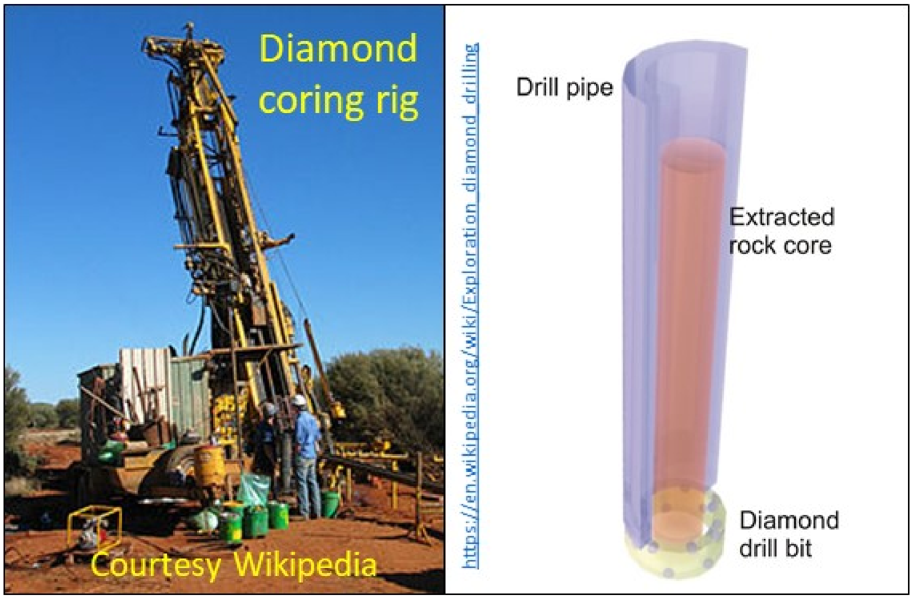



*Figure 2-9: Rotary diamond drilling for exploration boreholes in crystalline rock (Courtesy: Wikipedia)*

Another type of drilling that has been used in igneous and crystalline rock is the blind hole drilling method for ventilation shafts or "big hole" shafts for installation of elevators and ore lifts. This is a rotary drilling technique using a heavy drill assembly to thrust vertically. These bores are commonly drilled to provide deep shafts that allow ventilation, rescue shafts, service shafts (electricity, water…), ore lifts, or construction/mining personnel and mining equipment access to underground mining operations. The larger shafts usually involve drilling in multiple passes, gradually enlarging the borehole diameter and providing excellent deviation control because of the pre-drilled guide hole.

Figure 2-10 shows a hammer drill designed to use percussion methods to advance pier socket holes in a shallow marine application. This short height, hydraulically actuated drilling rig is not designed to drill deep holes, but is suitable for the particular need shown, drilling short sockets into hard crystalline rock to allow pier structures to be installed. The large cylinder above the bit and hammer drill is to provide sufficient compressive loading onto the drill bit face to allow drilling to take place without need for a pull-down load.

The drilling of an exceptionally large diameter hole usually involves a guide hole of small diameter, and subsequent advancement with a reamer bit, using the small diameter hole as a mandrel guide, thereby assuring that the enlarged hole is tracking exactly along the desired path. A guide hole is directionally drilled to follow a particular inclination far more easily than a larger diameter hole, and core sampling is straightforward. Shaft drilling has become more prevalent in the mining industry as it exposes workers to less danger than conventional drill and blast shaft techniques.


*Figure 2-10: Large diameter hammer drill and rig installing pier boreholes in crystalline rock (Courtesy: Atlas Copco)*

In existing mines, a technique referred to as “raise boring” is widely used to develop ore passes and other large-diameter (50-200 cm) boreholes between mining levels, or exceptionally between a deep level and the surface. In the raise boring approach, a pilot hole large enough to accommodate the drill pipe is emplaced, the drill rig is installed on the upper level, the drill pipe lowered through the completed pilot hole (typically 125-150 mm diameter) to the lower level, and the drill bit attached at the lower level. Then, the drilling rig applies hydraulic lifting force to raise the bit, cutting in an upward direction. The cuttings drop by gravity so there is no need to clean the hole, and the drill string is always in a state of high tension, rather than compression, therefore heavy drill collars to provide weight on the bit are not required. Although interesting, this approach cannot be used for a DBP repository because it requires a deep mine access to attach the bit at depth (“raise” boring).

Limited academic literature exists on the details of topics in mine drilling techniques because most of the developments are several decades old, or protected in a proprietary manner. Mining engineering conferences and the Society of Mining Engineers Handbook (Darling, 2011) contain useful information, and shaft drilling companies such as Herrenkneckt[23] and Frontier Kemper[24] advertise machinery to advance vertical shafts that are up to 9.5 m diameter and 1500 m depth. In general, it is best to contact service providers and equipment suppliers for details of capabilities.

A major line of development in the mining industry is the continued development of better hammer drills in strong, brittle rocks using air for shallower sections, and water for deeper sections. These hammer drills can be deployed in various configurations, with different approaches to fluid (air or water) circulation depending on the depth and related factors. Double-walled drill pipe methods can be used to permit cuttings flushing while providing high-pressure fluid to actuate the hammer, and it is feasible to use a custom-designed drilling fluid in some applications, although generally the preferred fluids are air and water as they allow the percussive attrition effect to be the most effective (viscous muds dampen energy transfer).

A widely publicized use of a moderate diameter borehole advanced with a hammer drill equipped with a mandrel to follow the pilot hole is associated with the 2010 Copiapo mining accident in Chile, where 33 miners were trapped underground. The miners were discovered through an aggressive exploratory drilling program using exclusively small diameter air hammer drilling, and were eventually rescued through a drill hole created by a specialized down-the-hole drilling hammer designed by Center Rock Inc. The bore was advanced from an existing guide hole of 14 cm diameter, first expanded to 30 cm in diameter, then to a diameter of 71 cm to allow for the steel rescue capsule on a wireline hoist to pass through. The final near-vertical borehole reached a depth of 628 m with an inclination of 82° and was drilled in approximately one month's time. The drilling history is summarized on a dedicated webpage of the Center Rock Inc. website.[25] Also, the Wikipedia site has a detailed description of the entire process, along with several excellent diagrams.[26]

## 2.6 Considerations for Deep Well Engineering in Crystalline Rock

Although there is considerable technology transfer between the construction process and technology used to drill boreholes in crystalline rock and wells drilled for oil and gas exploitation, the strength, abrasiveness, and hardness of crystalline formations necessitates stronger tooling and higher power machinery to be able to drill most effectively. Classical rotary methods are generally viewed more suitable for softer rocks (usually sedimentary strata), whereas brittle rocks such as igneous rocks or low porosity sedimentary quartzites and dolomites are more easily

[23] https://www.herrenknecht.com/en/

[24] https://www.frontierkemper.com/

[25] https://centerrock.com/

[26] https://en.wikipedia.org/wiki/2010_Copiap%C3%B3_mining_accident

drilled with percussive techniques. Nevertheless, technologies discussed in Chapter 1 are largely applicable with some modifications required due to the different rock types that may be encountered. Of interest is the marriage of rotary and percussive methods to try and take advantage of the benefits of each (Franca, 2011). Specifically, high-torque rotation gives a strong sideways thrust to the rock attrition process at the bottom of the hole, whereas the percussive action gives a strong brittle attrition component to the rock. Franca (2011) showed that a hybrid rotary percussion approach was effective in dense brittle rock, and less so in ductile rock. It is reasonable to surmise that this approach, which has made minor inroads in the oil and gas well drilling industry, will continue to develop with improved technology.

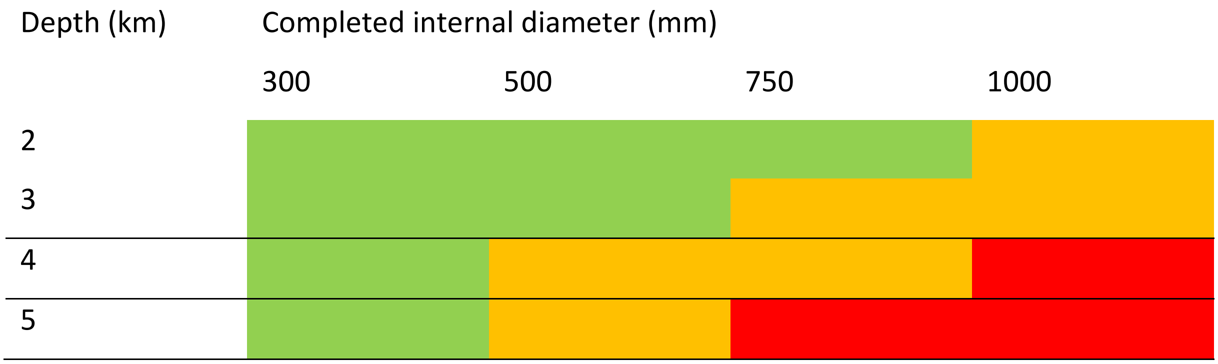
The idea of deep boreholes to isolate radioactive waste is not new. Beswick (2008) conducted an overview of the state of the art for technologies related to the construction of deep boreholes for nuclear waste placement. This review looked at key considerations and some conditions for placement that are likely achievable with modifications to existing drilling technology that is commercially available. The key considerations are highlighted in the following section.

The most important issue to review in the context of a DBP repository in crystalline rocks is the ability of drilling equipment to be able to advance large diameter boreholes to significant depth. This entails, as a performance minimum, a two-kilometer depth capacity for a 600 mm diameter hole size; although this is the capacity minimum envisioned, greater capacity systems are likely to be available, and for illustrative purposes, we use a one-kilometer depth borehole as an example DBP scenario.

Beswick (2008) noted that a 300 mm borehole is easily achieved up to depths of 5 km deep with currently available mining drilling technology under favorable geological conditions. The deep geothermal borehole drilled in Espoo Finland previously mentioned verifies that this may be viewed as achievable in reasonable quality igneous rocks[27]. Boreholes of diameters of 500 mm to depths of 4 km are likely feasible, but such deep large diameter holes are outside the bounds of known drilling experience in stiff, brittle crystalline rocks. Beswick (2008) states that although boreholes with diameters of around 750 mm and 1000 mm have been drilled, limited technical expertise exists for drill holes of this diameter to depths of perhaps two to three kilometres. These hole diameters are generally related only to the near-surface sections of oil and gas wells (i.e., the upper 1 km), or for limited-depth shafts for ventilation and services for underground mines (although raise-boring methods are more common when underground access is available). Table 2-1 outlines the feasibility of different borehole depths and diameters.

[27] Igneous (crystalline) rock masses are classified (see Chapter 4) as good quality to poor quality based on a number of observations on core, tests performed on rock samples, drilling data such as penetration rate (energy basis), and borehole geophysical logs. Espoo data have not yet been published.

*Table 2-1: Feasibility of drilled diameter for different borehole depths (Beswick, 2008)*




Key: **Green** = feasible with current technology and favorable geological conditions
**Orange** = may be achievable with tool and process development
**Red** = considered impractical in the foreseeable future

As a DBP repository large diameter borehole is advanced, different sized bits may be used, depending on the final design. Assuming that a crystalline rock repository is no deeper than two kilometers, the design scenario considered would be a surface casing hole to a depth of perhaps 200 m, and the emplacement hole of 600 mm diameter (base case scenario) to the total depth, and left uncased. Drilling of a large diameter surface borehole about 800 mm diameter to a depth of 200 m to place casing of 700 mm diameter to allow drilling of a 600 mm diameter emplacement hole is entirely within current technical capabilities. The actual relevant decision is whether to use rotary techniques or percussive techniques, or to consider the emerging rotary percussive integrated approach (Franca, 2011).

A key consideration noted is the requirement for high bit strength and designs for strong and abrasive igneous/crystalline rocks. Beswick (2008) states that usually bits used for hard formations and rotary drilling techniques are low to medium profile tungsten carbide insert bits. These bits require a high weight on bit and generally have low penetration rates, about several meters per hour. Rotary shaft drilling usually uses roller or plate bits organized in a specific array to optimize brittle crushing and chipping of the rock, rather than gouging or scraping. Multiple bits may be utilized to optimize the rate of penetration as different bits may be suitable to different lithological conditions (e.g. dense sediments over crystalline rocks). However, it is likely that this will not be a concern for a DBP at depth as a site with relatively homogenous repository rock is preferred and is likely to be mandated as part of the site selection criteria.

Consideration should also be given to the drilling of all large-diameter DBP holes with an initial guide hole; there are clearly additional costs, but important advantages, listed here:

- The guide hole can be continuously cored, giving a complete record of the geological conditions and the nature of the natural fractures along the entire hole.

- A small diameter borehole is far easier to drill at an inclination in a specific direction than a large-diameter borehole.
- A small-diameter guide hole can be wireline logged with a variety of downhole geophysical tools ranging from acoustic imaging and televiewer logs to density and mineralogy logs.
- A small-diameter guide hole is ideal for sampling fluid chemistry, evaluating rock mass characteristics and natural fracture permeability, and assessing homogeneity.
- The guide holes for a number of DBP boreholes can be predrilled so that there is less active drilling equipment on site, increasing safety by reducing the complexity of material and personnel movements.
- A pre-drilled array of pilot holes allows for cross-hole seismic, electromagnetic, and hydraulic testing, leading to a more detailed tomographic geological engineering model for the site that will guide the final placement design for each well.
- The guide hole serves as the guide for the drill to widen the hole to the larger design diameter so that the final large-diameter hole is exactly in the correct trajectory.
- A guide hole for each DBP well gives higher confidence in design of each future waste placement action for that hole, allowing flexibility on decisions to use or not use a particular section of a hole, without having to drill a large hole.
- If a small diameter hole must be abandoned, it is easier than for a larger-diameter hole.

The drilling of a DBP borehole should be completed in two passes, for these reasons, and Beswick (2008) also notes advantages of the guide hole approach because it allows for increased vertical control and confirmation of geological models developed at the location of the deep borehole. Some disadvantages noted by Beswick (2008) involve the potential for deviation of the subsequent reaming, although this can be eliminated through the use of a mandrel bit design.

A technology that has been gaining more use in hard rock situations in mining and in other domains is down-the-hole (DTH) hammer drilling. DTH hammer drills utilize a combination of hammering/percussion and some rotation to advance through the rocks using the power from the circulation fluid. Water hammer drills are generally more specialized than air hammer drills, with a limited number of companies producing them such as Drill King[28] and Wassara[29]. Most mining industry drilling companies produce some version of conventional air-powered DTH hammers, as these systems have a substantially higher rate of penetration than rotary drills in hard rock and are commercially available in a wide range of sizes for a potential DBP concept

[28] http://drillking.net/

[29] https://www.wassara.com/

hole. Hammer drilling is being adopted in the geothermal industry (Wittig *et al*., 2015) because the rocks encountered are generally dense, brittle and abrasive. Capabilities are being extended into steam projects, with large-diameter holes (e.g., 500-750 mm) more suited to the high flow rates associated with live (hot) steam.

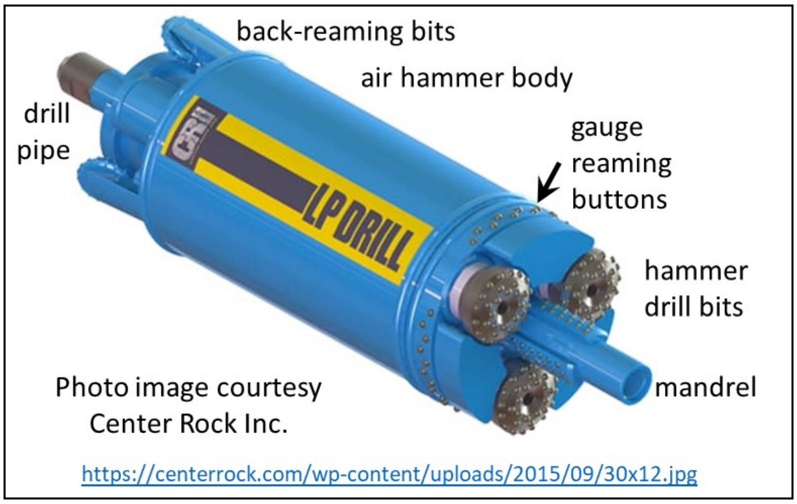



*Figure 2-11: Hammer drill for use with a pilot hole in crystalline rock (Courtesy: Center Rock Inc.)*

Figure 2-11 shows the details of a hammer drill of a diameter approximately the same as the proposed ≈600 mm DBP boreholes. The major characteristics to note are the central mandrel designed to follow the pilot hole, the gauge reaming tungsten carbide rim, and the back-reaming bits to cope with the possibility of drilling "out of the hole" if an obstruction develops (e.g. a small rock block falling on top of the hammer).

Using existing commercially available technologies, a custom-built drill rig will perhaps be required for the final implementation of the borehole array in a DBP repository. Custom-built rigs have been the norm for most scientific exploration projects and although it sounds technologically challenging, no new development of drilling technology will be required, just the use of already commercially available parts. Beswick (2008) notes that for large diameter boreholes to a significant depth, a substantial weight of downhole assembly and double walled drill pipe could lead to high lifting capacity requirement for a rig. This is discussed in greater detail in Chapter 5.

## 2.7 Summary

Precedent exists for deep boreholes in crystalline rock through rotary drilling techniques, and also through percussive hammer techniques. The advances made in drilling technology to facilitate the exploration of crustal rocks and exploitation of geothermal resources have led to larger diameter drill hole capacities, and the mining industry has been quick to adopt and adapt drilling developments for crystalline rock large-diameter hole drilling for ventilation and service shafts. Advancing boreholes of 500-750 mm diameter to depths of 4 – 5 km is within the capabilities of commercially available rotary technology; the depth capacities for large-diameter holes advanced with percussive drilling are lower, estimated at about two to three km, although for smaller diameter percussively drilled boreholes, depths of 6-7 km are currently demonstrated. A program like a DBP repository will not be undertaken without a detailed assessment of the various technical options, with view to the goal of achieving exceptional long-term security for the final repository. The choices for technology will reside on a more detailed study.

It is not entirely clear whether rotary or percussion methods will be adopted for large-diameter borehole construction, but both approaches have the necessary capabilities for the proposed design of a DBP repository presented herein, to a maximum depth of 2 km. The advantages and disadvantages of the various approaches must be the focus of a detailed study, with access to industry advice and information.

It is concluded that there is a reasonable probability that a custom-built drilling rig will be needed, or at the very least, a commercially available rig with certain modifications. This does not represent a technology barrier; all elements of the required technologies for a rotary system or a percussive system are sufficiently mature that a highly reliable solution to drilling will soon become apparent once design decisions are made for the physical parameters of the repository.

# Chapter 3: Well Plugging

## 3.1 Introduction to Well Plugging

Fundamental issues for radioactive waste isolation are the nature, quality and longevity of the sealing of the canisters at depth to minimize the potential for radionuclide escape. These seals must minimize the probability of leaks both around the well into the rock mass, and in particular must minimize the potential for leaks to surface or to the shallow meteoric groundwater zone[30]. Leaks are assumed to be radioactive materials dissolved in water and being transported by water.[31] The generation of a pathway involving only gaseous phase transmission, given the small natural fracture aperture and the small pore size of the borehole sealing and backfilling materials, is considered highly improbably because of capillary forces. This aqueous phase leakage can occur because of natural hydraulic (gravitational) heads that lead to slow water flow, because of buoyancy due to fluid density contrasts, or because of pressure contrasts arising from thermal or special hydraulic factors such as clay compaction or mineral dehydration. Leakage can take place along the well bore, through fractures generated by ancient geological events or enhanced by humans, or some combination of the two. In addition, these seals or barriers implemented to intersect, prevent or retard leaks should be inert over a long time span: thousands of years are needed until the most toxic radionuclides decay to minimal-danger levels.

These issues, except the last one, are commonly dealt with in oil well drilling and abandonment procedures. Casings are cemented during installation to provide zonal isolation, and when the well is plugged and abandoned, casings are removed (as much as possible) and replaced by a number of cement plugs to eliminate leaks. The oil industry has long experience in designing, installing, and verifying well barriers. This is considered a technology in itself, including plugging materials selection, equipment and methods of placement.

Due to the long timespan requirement for the barriers for radioactive waste isolation, we will not recommend using common cement but advise the use of materials that behave in a more inert manner over long time periods. Still, most of the barrier design will be developed using methods and experience from oil well drilling. Observe also that not just the seal, but the installation approach must be performed without failure. This is most probably achieved using existing experience and methodologies that have been carried out many times.

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[30] In this context “meteoric” implies Recent Age groundwaters that are circulating in the shallow zone and that have potential use for agriculture, pisciculture, human use, or are discharging into water bodies that could lead to exposures of humans or organisms to waste-sourced radionuclides.

[31] Radioactive gas leakages are less likely because gases generally can be assummed to dissolve in water durig transit; nonetheless, the issue of fluid buoyancy generated by small amounts of free gas remains a consideration, however remote.

In the following a review of relevant plugging methodologies from the oil industry will be given.

## 3.2 NORSOK Plugging Standard

In Chapter 1 we briefly looked at plugging of oil wells. In this chapter we will go deeper into oil well plugging. The general principles of redundancy, QC/QA, regulatory requirements, and professional design and analysis are appropriate for a DBP repository approach, as each individual placement borehole will have to be qualified and a sealing protocol established, verified, and implemented by professionals following regulatory guidelines. This modularity is considered to be a major advantage of the DBP repository approach.

The two-barrier principle is used throughout the world for petroleum wells. However, specific details are different and depend on the situation and risk. For land drilling, protection of fresh water zones is important in many places because these zones provide water for domestic and agricultural purposes; therefore, specific barriers must be used to protect these. For offshore wells in Norway this is not an issue, and even for some onshore locations in Norway where groundwater protection is not an issue.

In 2009 there was a substantial oil well blowout in the Gulf of Mexico, the Deep Water Horizon rig in the Macondo Field. After this accident, many regulations were rewritten and sharpened; yet, there is no common set of regulations that has been adopted; regulations still vary somewhat from country to country. In the North Sea, different regulations apply between Norway, the UK, Denmark, Germany and the Netherlands, although there is a great deal of commonality.

"Norsk Sokkels Konkurranseposisjon", the Norwegian initiative to reduce cost on offshore projects, was established in 1993 and named NORSOK. Initiated by the government, it is a cooperative project involving the oil industry, the service industry and labor organizations. The standards are developed by these parties with heavy involvement of the oil industry. Over the years the NORSOK D-010 Well Integrity standard has been developed. It has evolved into a systems approach, and is today considered one of the most rigorous standards worldwide, and is used by many outside Norway. We will review this standard from the perspective of radioactive waste placement in boreholes.

The elementary principle behind NORSOK is that all petroleum wells shall have two independent and tested well barriers at all times. If one barrier fails, the second is relied upon only until the first barrier is restored, and then the operation continues. In practice this is today handled by developing individual barrier diagrams for each well operation, and the barrier scheme must not only meet regulatory requirements, it must be approved by the responsible professional people involved who study and document the plan. Earlier tendencies for human mistakes have been reduced considerably by establishing the NORSOK D-010 standard.

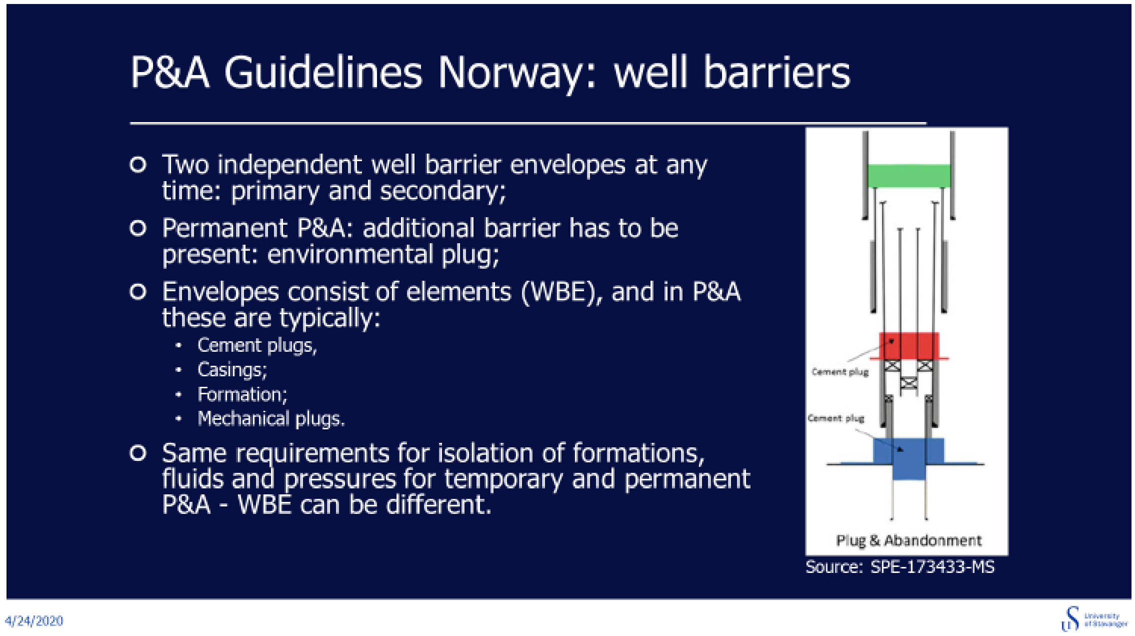


*Figure 3-1: General two-barrier principle for petroleum wells.*

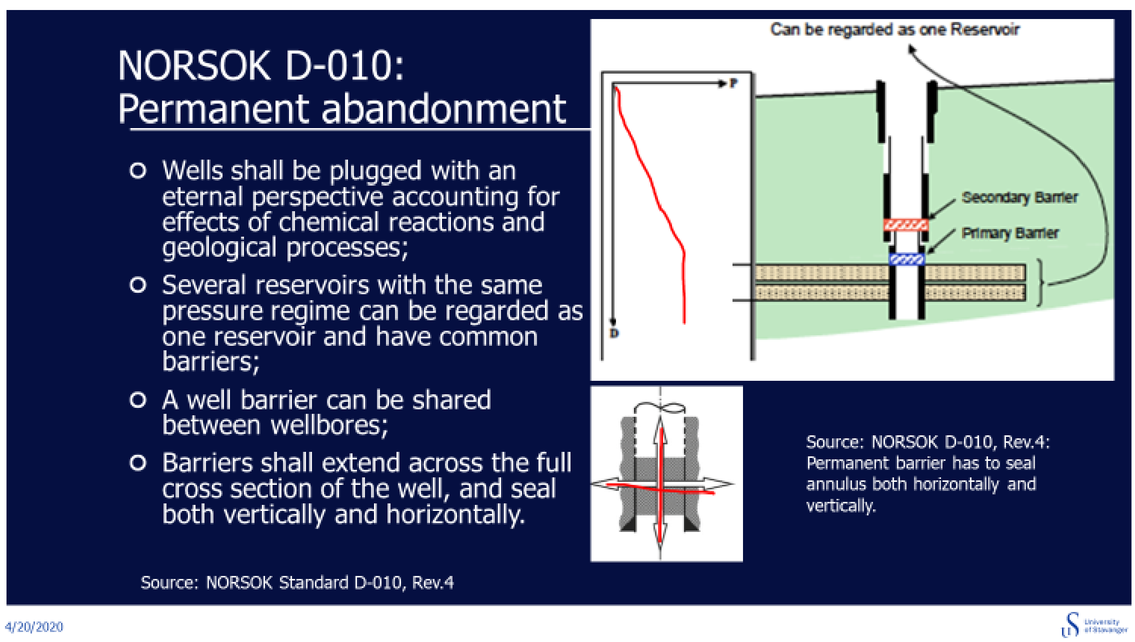


*Figure 3-2: Principles for permanent plugging and abandonment*

The concern during well operations is mostly about upward leaks along the wellbore, although intraformational leaks also should be assessed (i.e., flow from one zone into another at depth). Basically, the barriers provide assurances, particularly against within-casing leaks (inward or outward), along the pathway from the reservoir to the surface. On the outside of the O&G

wellbore, steel casings and cement are installed, tested and are expected to function as barriers between the fluids in the wellbore and the external rocks, which themselves may contain pressurized fluids or which may consist of highly permeable zones that would lead to loss of valuable hydrocarbon fluids.

During permanent plugging and abandonment of an oil well, a gas well, or even a dry exploratory well, the situation is different. First, most of the casing is cut from the well and removed to allow for the plugs to be installed directly against the rock, to isolate zones and inhibit the development of pathways along the exterior of the casing (Dusseault and Jackson 2014). In the present context, we have a long-term perspective and also wish to consider potential long-term leaks between reservoirs, illustrated with the two arrows in Figure 3-2. The plugged well has a minimum of three barriers, the two main barriers and an environmental plug near surface. We note that in the case of radioactive waste placement we have a much longer timeframe perspective, exceeding a thousand years.

## 3.3 How Good are Oil Well Barriers?

There are many challenges in establishing good barriers in O&G wellbores for final abandonment, several are listed below.

- During initial placement of the cementitious barrier behind a casing, the cement may be polluted by the drilling mud it displaces and by the presence of an incompletely removed wellbore wall mud cake, leading to an incomplete contact between the cement and the rock or the cement and the casing, or the creation of channels through the cement.
- Cement shrinks when it sets and may therefore establish microannulus pathways between the cement and the rock, giving leak potential over time (Dusseault and Jackson, 2014). Remnant drilling mud will also shrink, helping generate pathways.
- In old wells that were plugged decades ago, the cement is sometimes shown to be chemically degraded, particularly by acidic materials, indicating a severely limited lifetime in practice for standard oilfield cements.
- Natural gas buoyancy means that slow upward migration of gas along the wellbore trajectory can take place at low levels, and significant gas emissions may not develop for decades until they are evident at surface.
- In many sedimentary basins, including offshore Norway, the pressures at depth, even in thin water-bearing and gas-bearing zones, can be much higher than hydrostatic (10 kPa/m), so that even once a barrier is firmly established, there remains a residual tendency for flow that persists indefinitely.

Cement is the most used barrier material. It is relatively cheap but has recently come under more criticism for not being good enough in cases where the prevention of long-term leaks is essential (e.g., areas containing old abandoned oil wells that are now undergoing urbanization). Today there is considerable research taking place for the identification and testing of alternative barrier materials. We will below discuss a few that have relevance for radioactive waste placement and isolation.

The rocks that O&G wells pass through typically consist of 70% clays or shale. Especially at shallower depths (several kilometers), these fine-grained strata usually contain chemically reactive clay minerals such as smectite (montmorillonite), mixed-layer clays and vermiculite.[32] In contact with water and under the low matrix stresses in an exposed wellbore wall, clay minerals may swell, especially smectite. Because these rocks are also weak, this swelling may be accompanied by plastic yielding, which also tends to generate an increase in volume and thereby help plug the hole in a time-dependent manner. This property of volumetric increase from swelling and yield is considered to be a potentially useful barrier in North Sea wells, to some extent replacing cement. Although not yet fully proven, the idea of using the rock in-situ as barrier material is interesting (Xie, 2019). If deep placement in sedimentary rocks is allowed, this consideration has merit as one of many sealing approaches; in the DBP repository concept for Norwegian radioactive waste placement onshore, it is not an option: no such sedimentary sequences exist onshore Norway, and offshore placement is not allowed.

Typically, in an O&G wellbore plug installation, only one type of material is used. However, there is an interesting alternative called the "Sandwich" method. Q-pack is a slurry mostly consisting of natural quartz. It does not solidify, but packs off mechanically because of a carefully chosen grain size distribution where small grains block larger pores, reducing the permeability to a low value, and also providing a strong capillary barrier to gas flow because the quartz is water-wet and the pore throats are small. One application mode is to first place cement, then a Q-pack pill, followed again by cement on top. This principle introduces redundancy in the plugging process, and it also incorporates a mineral plug using a material (quartz - $SiO_2$) that is extremely geochemically stable.

An older method is to make a plug of finely-ground barite ($BaSO_4$). This is a mineral of density 4.48 times the density of water. Because of its high weight it will go to the deepest position in the well, and the high weight tends to help retain the pressures at depth and resist flow.

Once in a densely-packed state in a wellbore, such granular materials, without additional cementitious agents, provide frictional restraint against the wellbore walls, and hence retain their integrity.

### 3.4 Radioactive Waste Isolation Plugs

Knowledge and technology from the oil industry will help ensure that high quality permanent plugs of indefinite life span are established in DBP repository boreholes. However, due to the

[32] Other clay minerals such as illite, kaolinite, and chlorite, generally are not regarded as "reactive", and have much lower cation exchange capacities than the "reactive" clays.

severity of the environmental constraints and a longer time perspective, additional concerns exist for radioactive waste placement boreholes. Some of these issues are:

- The number of plugs might be increased, and eventually the entire borehole may be backfilled to the top with plugging materials that are not cementitious, but which can be removed if necessary to access the placed wastes. Technologies such as granular $SiO_2$ or $BaSO_4$ placement can be emulated; in a retrieval operation, these materials can be jetted, suspended, and pumped out of the hole.
- A sandwich method should be used to provide different types of barriers to different processes. For example, capillary barriers (small pore throats in a porous substance) are effective to exclude gases if the granular materials remain water-wet. Other barriers can be designed to have zero permeability to aqueous solutions. This implies using several different plugging materials and zones stacked on top of each other providing redundancy if one material fails for physical or chemical reasons.
- The plug material should be relatively inert and not change significantly in nature or volume if exposed to natural waters, to the chemical factors associates with canisters and the materials within the canisters if these are breached, or to the effects of irradiation from high-energy radioactive decay processes, including any thermal effects.

## 3.5 Review of Plugs Commonly used for Radioactive Waste Isolation

Freeze *et al*. (2019) provide a review of the safety aspect of deep "disposal" boreholes;[33] their paper outlines the safety assessment needed for such cases. Most sealing methods for hydrocarbon and geothermal wells are based on inorganic, man-made setting materials, although other methods use swelling materials (swelling polymers and clays), packers, resin and asphalt. Regarding plugging materials, they list a number of options, and we have amplified on the discussion of the geomechanical properties of these materials and their suitability in a nuclear waste repository setting. A comprehensive listing of chemicals used in drilling muds, for sealing wells, and as additives to cement in the oil industry can be found in Fink (2012).

*Cement*: The most commonly recommended plugging material for use in radioactive waste isolation. This material has challenges such as placement quality (mix consistency and density), borehole quality, thickening behavior, and setting times. It also shrinks sometimes, particularly if the slurry is a neat cement-water slurry, if the plugging material is placed at too low a density because of mixing errors, and if there is premature exposure to NaCl or other agents. All these processes potentially lead to the creation of microannuli, thin, partly circumferential openings between the rock and the cement, or between the cement and the casing. Freeze *et al*. (2019) nonetheless conclude that even with the complexities considered, cement can be a useful

[33] We avoid the use of the word "disposal" because it has some implications of permanence; the DBP borehole isolation method we discuss is designed to allow retrieval of waste canisters.

component of the plugging process. Here we note that in the O&G industry, particularly with thermal wells that will be exposed to temperatures exceeding 300°C during steam injection, high-silica cement is used, and up to 70% of the cement powder is replaced with silica ($SiO_2$) flour, which is merely very finely ground quartz. In other applications where sulphates are encountered (gypsum) or where hydrogen sulfide gas in solution may lead to acidic conditions, sulphate-resistant cements are available. A simple policy for cements in long-term application such as use in radioactive waste repositories is to use cementitious slurries with as little cement powder as feasible, because it is the cement phase itself that is geochemically unstable, not the inert mineral filler.

There are different grades of cement powder for different applications, and there are also different grain sizes of cement powder, only rarely used in O&G drilling and completions. The latter are used for grouts in the civil engineering rock mechanics industry, and touted for use in the nuclear waste placement and isolation industry (e.g., Bhasin *et al*., 2002; Ahrens and Onofrei, 1996). Specifically, "microfine" and "ultrafine" are finely-ground versions of conventional cement powders that penetrate into smaller cracks in a jointed rock mass when used as the solid phase in a cementitious grout. Although these have proven highly effective in many applications, geochemical stability of cementitious materials remains an issue.

*Bentonite and Other Clay-Based Systems*: Bentonite is a widely used O&G industry term that describes a rock-type that is high in swelling clay mineral content (usually smectite) and tends to expand substantially when in a stress-free (unconfined) state and in contact with water. Finely-ground dry bentonite is the material used to formulate aqueous-base drilling muds. Bentonite generally has over 80% smectite clay mineral content, and the sub-type of smectite that is the most common in bentonite is montmorillonite. Once dry ground bentonite is exposed to water and swells, the clay paste has a low permeability because of the small grain size of the clay particles (< 2 µm). The clay paste is also "plastic" and has good self-healing properties. One technique for plugging shallow lost-circulation zones in drilling O&G wells is to disperse bentonite-based drilling clay, a fine-grained dry powder, into a mineral oil (diesel fuel was commonly used) to create a relatively dense slurry. The oil protects the clay from immediate hydration and swelling, allowing the slurry to be injected through the drill pipe adjacent to the lost circulation zone where exposure to water turns the clay into a plastic paste hard enough and stable enough to block the large channels and pore throats in the lost circulation zone. A useful demonstration of the swelling behavior of bentonite clay is to disperse 150 g into 100 mL of paraffin oil, then stir in 200 mL of fresh water. The result is startling.

There is considerable merit in incorporating clay minerals in one form or another into the materials used in isolating radioactive waste in deep boreholes. Their swelling and plastic characteristics are outlined above, but they also possess another valuable characteristic, the ability to adsorb cations from aqueous solution. These may be radioactive cations that have escaped containment, and their adsorption means they are no longer free to move, essentially immobilizing them, or at the least, massively retarding their movement, thereby allowing radioactive decay to inconsequential levels of radioactivity.

*Geopolymers*: These are cement derivatives produced by alkali activation of Class C fly ash with a NaOH and sodium silicate solution. These products are in an early stage of development and are not yet qualified for use in long-term sealing roles. Their geochemical stability and sensitivity to temperature remain to be defined under conditions similar to a DBP repository, although we note that any DBP repository onshore Norway is highly unlikely to encounter high temperatures, oxidation conditions, or soluble minerals except perhaps fracture-filling minerals such as gypsum ($CaSO_4.2H_2O$) or calcium carbonate ($CaCO_3$).

*Silicone Rubbers*: These materials are used in conjunction with cement in gas wells to create a containment material for the casing that is impermeable to gas. It is stable at high temperature. There are many other patented additives used in oilfield cement that purport to give much better sealing qualities, including latex additives and various materials that will promote the slow blocking of pores within the cement over time (Fink, 2012). However, the long-term chemical stability of these products remains to be established in the context of residence time requirements in the range of thousands of years in the geosphere.

*Natural and Man-Made Asphalt*: These materials are insoluble in water, non-crystalline, chemically inert, ductile under mechanical loads, and softening with higher temperatures. They may have placement challenges in aqueous environments, and might complicate predictions of long-term radionuclide transport. Nevertheless, the exceptional properties of asphalt and its clear long-term stability underground make it a leading candidate for sealing DBP repository boreholes. Natural asphalt (gilsonite) veins millions of years old testify to its stability in the geosphere (Crawford, 1949).

*Crushed rock*: This has been used as a seal in hydrocarbon wells, often in conjunction with other granular materials such as sand and clay. It might be difficult to obtain a good absolute seal against any fluid transmission, but a well-graded material, constituted with an appropriate range of grain sizes ranging from a few microns to a few millimeters, can achieve a high density of placement, and this density can be enhanced through physical compaction or vibration while being placed. In civil engineering applications such as road subgrade construction, a well-graded and mechanically densified layer is critical to the overall road stability. In some applications, a small amount of binder (e.g., 2% cement or some asphalt) is added, but the strength of the material is almost entirely the result of the density, giving excellent frictional resistance. Rock cuttings from percussive drilling can serve as the basic material, with the addition of a finely ground clay mineral such as illite, vermiculite or chlorite. An issue here is that these materials cannot be deposited under water, allowing sedimentation, so that the different sizes separate again. Advantages of crushed rock include availability and cost, geochemical inertness, ability to create a well-graded granulometry to achieve high density and small pore throats, good compaction response, and retrievability.

*Quartz-Pack™*:[34] This is a proprietary mineral-based sealing system consisting of a mixture of barite, bentonite and up to 75% fine silica. It does not set because there is no cementitious additives, and will therefore deform rather than crack if the borehole deforms. It is chemically inert, comprising only stable minerals. Recently this product has shown good results when used in conjunction with cement plugs (Saasen *et al.,* 2011). These materials are often used in the "sandwich" approach to well sealing, mentioned earlier.

*Ceramic seals*: A ceramic plug is placed within the borehole and expands upon intense heating through use of the strongly exothermic thermite reaction ($Fe_2O_3 + 2Al \rightarrow Al_2O_3 + 2Fe$) that does not require external oxygen sources. These are promising plug materials, and the heat generated is short-term and highly localized, so the thermal shock to the surrounding rock is not as extensive as rock welding (see below). These are in early stages of development, field proof of efficacy and longevity remains sparse, and efficacy if there is water in the hole is an issue.

*Rock Welding*: Rock welding uses downhole electric heating to partially melt and recrystallize crushed granite backfill. This can create a strong and durable plug; however, the high temperatures involved lead to thermoelastic expansion in the near-field rock mass that is not melted, and this leads to crystal debonding, thermal cracking, differential stresses, and potentially increased permeability in the crystalline rock that compromises the isolation of the wastes. Extremely high temperatures and melting sound like an attractive approach to a seal, but there are complications, and retrievability issues also arise.

There are many other sealants and chemicals used in the O&G industry; in the civil engineering industry, applications of various grouting materials in naturally fractured rock masses to seal and strengthen them has a history of well over 100 years. Sodium silicate grouts have been used for decades to seal joints and rock pores in civil engineering projects, and silicate-based drilling fluids (e.g., van Oort *et al.*, 1996) have been used in O&G applications for over 30 years. These systems, among many others, are deserving of re-examination for potential application to indefinite reduction of permeability (fracture conductivity) for nuclear waste placement in deep boreholes in naturally fractured rock masses.

## 3.6 Design of Plugs for Radioactive Waste

Plug design from the O&G industry forms a good basis for design of plugs for radioactive waste isolation. A summary is given below.

- The oil industry has significant experience in improving rock conditions around wellbores with chemicals and physical agents to block permeability and help stabilize the wall of the borehole.

[34] https://www.flopetrol-wb.com/

- The O&G industry has a long history of plugging wellbores with chemicals and with setting agents (cements, resins). One aspect of risk in the borehole plugging and sealing is the substantially larger diameter of the repository borehole compared to oilfield wellbores. This results in the potential for operational failure, leaving the radioactive waste canister not fully secured, and therefore difficult to seal and plug. Appropriate placement methodologies from the O&G drilling and careful borehole management techniques can be modified for canister placement and sealing.
- In addition to oilfield cement, used for casing cementing and plugging holes in formations, sealing perforated intervals, and so on, special resins and materials used for squeezing behind casing or within the borehole have been developed by the O&G industry.
- The O&G industry also has developed a wide array of rubber, polymer, and even steel packers for sealing off zones in or behind casing, including physical (mechanical) devices such as metal or plastic bridge plugs that are set with weight to seal against the inside of a steel casing, or even against an open borehole wall.
- In particular, oilfield expertise in the placement of granular materials such as silicate type particles have potential for DBP borehole backfilling, as they are geochemically inert, resistant to any tectonic or thermal disturbance (no seal impairment), do not require a setting agent, and also allow straightforward retrieval of waste canisters through jetting methods.
- From redundancy considerations in the O&G industry, it is proposed to use a sandwich approach, i.e., by stacking two or more different types of plugs on top of each other, for sealing of each high-level waste canister. Less stringent sealing requirements can be developed for intermediate- and low-level waste capsules if the DBP repository concept is also used for these materials.
- All chemical, mineral and mechanical plugs must be compatible with the geological environment; this means chemical compatibility with rock and geological fluids, but, particularly in close proximity to waste canisters, it also implies compatibility with respect to ionizing radiation and the designed temperature changes arising. In transitions from one sealing material to another along the axis of the DBP borehole, they should not violate the mechanical function nor the chemical inertness of the plug.

In brief, before any significant decisions are made, an in-depth revisiting of all proposed nuclear waste sealing systems in competent rock masses should be undertaken, but including all the O&G industry developments in this area, including the methods of seal placement.

# Chapter 4: Site Qualification

## 4.1 Overview of Site Qualification

The goal of site qualification (both technical and social) is to evaluate and assure the suitability of a location for the long-term placement and isolation of nuclear waste such that it "qualifies" for development as a repository. If there is a "host community" for the DBP repository (e.g., a local community or social group), an over-riding qualification criterion is that the community is willing to accept the potential location of a deep repository, pending the outcome of the evaluation and technical qualification process. In this context, the process of siting is as much a socio-political issue as it is a technical issue, and there is a vast body of literature related to these factors (e.g., Kraft and Clary, 1991; Sjöberg and Drottz-Sjöberg, 2001). As the socio-political aspects of repository selection are outside of the report remit, socio-politically related risk assessments and issues will not be further addressed in any detail. Recent divergences of opinion within a local community in Canada and its constituent social groups suggest that technically optimal sites may not be qualified (i.e., acceptable) from a social-political aspect.[35] This possibility must be kept in mind in developing the site qualification specifications.

However, there are technical risks that will be gradually quantified during the process of site selection and evaluation; these should be identified and specified as much as possible within a formal and on-going QC/QA process, and the principles of Adaptive Management (Williams *et al*., 2012; Linkov *et al*., 2006) must be implemented to guide the process. It is important to acknowledge and plan to accommodate the increasing amount of technical information that is generated throughout the process that will potentially alter the perceptions of risk. To emphasize this issue of site selection risk, the Yucca Mountain repository project in the United States is an important case history. As more geoscience data gradually emerged, it became apparent that the level of predictability stipulated by governments could not be met, and the project was cancelled in 2009 (Rechard *et al*., 2014). This constitutes a case history of adaptive management of risk, resulting eventually in the disqualification of a site. Importantly, disqualification must remain an option throughout the project, even extending to the qualification process for individual waste placement boreholes.

The site qualification process involves multiple stages of screening sites for suitability based on increasingly rigorous criteria as the number of suitable candidate sites diminishes through a process of elimination. Depending on the phase of site qualification, the data used to rank site suitability are based on more-and-more comprehensive and quantitative information that is increasingly derived from on-site subsurface sampling and testing programs. These screening activities are continuous throughout the process, and it is important to recognize that the final

[35] https://www.neimagazine.com/news/newsindigenous-community-rejects-waste-repository-plans-in-ontario-7753680#:~:text=The%204500-member%20Saugeen%20Ojibway,170%20for%20and%201058%20against .

siting and design of a DBP repository is a socio-technical process, not based on an initial rigid choice of outcomes. Adaptability should be an element of the site qualification process.

Stated otherwise, before detailed site characterization from a technical standpoint takes place, initial screening actions are high-level and broad-ranging evaluations that take into account sociological, geographic, historical, demographic and geological factors. For example, typically a high-level decision-making site selection committee will be formed, comprised of a group of technical persons with the appropriate backgrounds who, with the advice of other experts, develop broad criteria for many important parameters. A few examples of the broad suitability criteria that the committee might consider are listed here:

- *Site Accessibility*: This relates to ease of personnel and equipment access and work tasks, leading to favoring of sites that are reasonably flat-lying, close to all-weather transportation routes, and unimpaired by seasonal flooding, ice-jams, and other natural hazard risks.
- *Proximity to Population Centers, Popular Areas, Infrastructure*: This set of criteria might be expressed in many different ways, but could, for example, be simple prohibition such as not within 10 km of a park boundary, 10 km of a centre of more than 1000 population, etc. Alternatively, a weighted geographical suitability function can be developed based on proximity to population concentrations, parks, frequently travelled roadways, tourist activity, agricultural regions, and industrial sites (mines, quarries, military and defense establishments).
- *Surface Water Interaction*: Site location with respect to drainage pattern and features such as lakes, rivers, wetlands, fjords, and the seacoast may be developed into a set of siting criteria.
- *Subsurface Water Interaction*: First-order assessments of groundwater flow, based on available domestic water well data and elevation analysis, can serve as a site suitability metric basis, with sites having artesian conditions less favored, strong discharge areas prohibited, etc.
- *Legacy Activity*: Existence of legacy mining activities including exploration boreholes, old adits or drifts, old open pits, and other unspecified subsurface structures can be factored into the set of suitability criteria for site qualification.
- *Geological Features*: Identification of known faults, deep seismicity, karstic features, extensive mineralization, deep weathering profiles or other geological features that could detract from site suitability will be necessary, and may lead to exclusion of locations if the features are significant.

It is expected that, after this broad but vital assessment, a short list of sites or areas will initially be proposed as suitable candidates for hosting the DBP repository; at this stage, the technical assessment begins in earnest. As these sites have been screened at a high level by the project client and the technical committee, the next phase is to devise a quantitative scheme for short list evaluation before a preferred site (or two sites) is selected for qualification. The quantitative scheme is designed to take into account many technical factors of varying levels of impact; the process will allocate the level of impact through ranking and weighting factors that are decided by the technical committee and by gathering and analyzing the advice of various experts. This process leads to a semi-quantitative rank ordering of site suitability based on the evaluation metrics, and one or perhaps several sites will be selected for further study (e.g., see the ranking methodology presented in Nadeem and Dusseault, 2007). Various tools are available for further input of expert advice to aid the decision process, such as review panels, or even formal expert elicitations (Larkin *et al*., 2019). Various tools, usually of a GIS (Geographical Information Systems) nature with multiple criteria, are available to guide this process.

The preferred sites will then undergo a geological exploration program involving surface methods and potentially advancing a pilot boreholes to characterize the site geology and subsurface, while developing an integrated technical model of the site. One may assume that this geoscience-based screening process leads to a single preferred site, although in the case of nuclear repositories it is important to keep options open to allow flexibility as more geological information becomes available.

It is imperative to the success of any nuclear waste placement and isolation program that a synthesized Geological Engineering Model (GEM) of the site is developed at an early stage, and that this GEM continues to be populated with more information from boreholes and geophysical methods as such data become available. The GEM can be used to generate sub-models to aid in design of the borehole infrastructure and develop a safety case for the DBP repository concept.

This chapter focuses broadly on all aspects of the site selection process including factors for selecting candidate sites, preliminary testing programs for candidate sites, and potential testing programs for characterizing the subsurface for design of the DBP boreholes. Government, academics, and consultants working on the placement and isolation of nuclear waste have developed guidelines for site selection requirements and site characterization. Further to this, detailed site characteristic plans exist and are available to aid in designing a future program for the DBP project. This chapter uses some international and Canadian examples to develop a qualitative Site Qualification Workflow to assist in planning.

However, this is preliminary work only. If the DBP repository concept is to be further advanced, the subjects and methods mentioned in this chapter must be revisited in detail. This includes a comprehensive review of the information collected to date for other similar sites around the world that have undergone varying degrees of site qualification investigations, ranging from preliminary exploration to actual placement of nuclear waste.

## 4.2 Preliminary Site Review

At the preliminary site review phase, multiple candidate sites are identified that meet the first set of ranking parameters (e.g., accessibility, distance from population centres, etc.).

Geographical Information Systems (GIS) multi-attribute mapping is the preferred tool for overlaying the spatial results of assessments to allow focusing on regions that are highly ranked (Drobne and Lisec, 2009).

More detailed and rigorous criteria are gradually applied to winnow the multiple sites into a handful (3-6) for ranking of suitability as a DBP repository location. An expert elicitation process that involves risk estimation by knowledgeable persons may enhance the utility and applicability of these criteria (Larkin *et al*., 2019), and semi-quantitative ranking schemes are generally developed or approved by the technical committee. At this phase, site investigation will likely include desktop surveys, along with site visits and direct evaluations and ranking of sites by selected experts in various domains. The technical committee to oversee the process is formed as a guidance body for the owner of the repository and the contractors, and it will comprise appropriate technical experts in the sciences, engineering, risk analysis, and management domains.

The IAEA (2011) has outlined a list of technical and non-technical factors to aid in determining a shortlist of candidate sites (Table 4-1). Characteristics that are clearly unsuitable should automatically preclude a site from being shortlisted (sometimes called "go/no go" criteria).

*Table 4-1: Technical and non-technical factors for site suitability*

| | |
|---|---|
| **Technical Factors** | |
| **Suitable** | **Unsuitable** |
| ▪ Geological stability<br>▪ Geomorphological stability<br>▪ Arid areas<br>▪ Absence of natural resources (mineralization, oil and gas, geothermal)<br>▪ No previous mining or sub-surface exploitation | ▪ High volcanic or tectonic activity levels<br>▪ High erosion potential, steep topography<br>▪ Flood plains/surface salt deposits/low-lying sea inundation or storm-surge risks<br>▪ Minerals, gas, geothermal or water resources present (where water is in short supply) |
| **Non-technical factors** | |
| ▪ Government-owned land<br>▪ Distant from national boundaries<br>▪ Land far from population centres<br>▪ Sites with sufficient information available | ▪ National parks/nature reserves/indigenous lands<br>▪ Land close to disputed boundaries<br>▪ Proximity to highly travelled routes<br>▪ Areas of touristic interest<br>▪ Areas of high population density<br>▪ Comprehensive lack of information |

(Modified and extended, but based on IAEA, 2011)

Suitable sites are those that do not include any of the unsuitable technical and non-technical factors.

Once a shortlist of suitable sites is developed, consideration is also given to longer-term issues related to post-closure safety requirements because of complexity, cost, convenience, risks of future development or breaching by human activity, and so on. The IAEA (2011) outlines a list of factors that could eliminate shortlisted sites based on post-closure safety issues (Table 4-2). The major factors to consider are the long-term geological stability of the location, geochemistry, and site hydrology. Note that these factors can all be expressed quantitatively, such as the stipulation of a minimum level of rock matrix strength (unconfined compressive strength). After considering these additional factors in more detail than the preliminary sites reviews, the shortlist can be revised to focus on a few remaining candidate locations.

*Table 4-2: Post-closure safety factors to eliminate shortlisted sites*

| | |
|---|---|
| Stability | ▪ Geology is unstable, i.e., active fault or seismicity close to the site<br>▪ Geomorphology or observed slope instability suggests some erosion risk down to the top of the isolation zone over the timescale of interest exists<br>▪ Volcanic activity risks exist for the projected timescale |
| Geochemistry | ▪ Unsuitable groundwater or porewater chemistry for canisters and buffer material integrity assurance<br>▪ Unsuitable groundwater age that implies active meteoric water circulation systems of short timescale<br>▪ Evidence that, on the timescale of interest, the geochemistry could change to an unsuitable state |
| Hydrology | ▪ High rates of rainwater percolation, groundwater flow, and weathering so that, over the timescale of interest, the weathered zone would extend down to the isolation zone |

(Modified and extended, but based on IAEA, 2011)

## 4.3 Surface Geophysical and Geological Program

Surface geophysical and geological mapping programs are the main tools to narrow the candidates at the stage where multiple candidate sites exist. Even if only one candidate site exists after the preliminary review phase, a surface-based program should be completed prior to any pilot borehole drilling and associated testing programs. Because of the risks entailed in placing all activity at one site that could potentially be disqualified as more data becomes available, it is preferable to have two or three sites, with the majority of the qualification activity taking place at the highest-ranking site as time goes on.

Existing airborne or ground-based geophysics techniques such as magnetic surveys, resistivity surveys, gravity surveys, and seismic reflection are useful to assess large-scale anomalies, structural trends, and basement topography if drilling through sedimentary cover into dense igneous and metamorphic rocks. A geophysical program involving some combination of the above-mentioned techniques in aerial and land-based form is employed to gather non-penetrating information about the subsurface, constructing the first version of the site GEM based on surface mapping and sub-surface geophysical data. An advantage of geophysical surveys is that a GEM of the site that extends some distance in all directions beyond the repository boundaries is developed, allowing the detailed borehole data that is collected later to be more easily interpolated between boreholes and extrapolated beyond the drilled area, identifying anomalies that should be investigated. A GEM based on high-resolution geophysical data also reduces the need for boreholes far beyond the repository boundaries, although it is acknowledged that in dense rocks boreholes are potential future pathways for radionuclide migration and their number should be limited so that the most promising drilling locations are surrounded only at some distance by such exploratory boreholes.

A surface geological and structural mapping program is undertaken in conjunction with geophysical surveys to aid in interpretation of the data and give clues about the subsurface disposition of rock structures and rock types. The mapping programs will be utilized to determine the presence of any regional scale structures (faults, folds, etc.) and spatial variation of lithological units at the site. The presence of unsuitable structures determined in the mapping at this stage would likely preclude a site from being selected, before the expense of drilling exploration boreholes. For example, if a through-going fault zone with somewhat permeable gouge is discovered, it would likely disqualify the site, or downgrade it substantially. We note that in crystalline (granite batholithic) sites, such faults are well-known, but usually widely spaced such that suitable repository conditions can be found (Černý *et al*. 1987).

Using these preliminary geological site models, sites are ranked based on their geological suitability. The integrated combination of data from the geophysics and geological mapping programs provide the basis for the GEM of the candidate sites, and this GEM will be tested and refined as the DBP project advances. The GEM will also be used to guide the downhole testing activity associated with the pilot hole stage of site characterization, outlining locations, and aiding in the qualification of each individual high-level waste isolation borehole.

## 4.4 Pilot Hole Program

A sequence of pilot holes will be advanced at the final selected sites to allow for the collection of geological, geochemical, hydrogeological, and geomechanical data to guide site suitability decisions. This data will be incorporated into the GEM for each site to provide enhanced knowledge that will aid the decision as to which site will be chosen as the primary repository site, and therefore be the focus for more detailed characterization. Each of the pilot holes will be used for intense rock mass characterization, including at least the following activities:

- Full-depth oriented coring for most or all of the pilot holes;
- Overcoring stress measurements at selected depths;
- Measurements while drilling, including geolocation data, weight on bit, rate of penetration, and drilling fluid losses (indicative of natural fracture conductivity);
- Geophysical borehole logging with a comprehensive suite of open-hole geophysical logs;
- Borehole televiewer and ultrasonic scanner logging and image analysis;
- Full profile fracture hydraulic conductivity testing over zones no more than 10 m in length and some thermal tests for thermal conductivity determination;
- Detailed core assessment for mineralogy, fabric, and geomechanics properties; and,
- Cross-hole seismic and electromagnetic profiling when two or more holes are available.

Each pilot hole will eventually be used as a monitoring hole for the DBP repository construction life, and perhaps well beyond, to help confirm modeling predictions.

Before the first pilot hole location is chosen, the preferred repository layout on the site is approximately delineated. It is suggested that this layout be roughly an ellipse or circle (Figure 4-1). The layout shown is a circular array of 36 final isolation holes, with each hole at 10° rotation from the previous hole and inclined 10° outward. This array provides for sufficient distance at the surface (≈7-8 m) between each borehole that surface activity (drilling, transportation, wireline placement of canisters…) can proceed unimpeded. Surface accessibility and a sufficient central work area are, of course, part of the criteria used for initial site selection. It also assures that spacing between canisters at depth is so large that thermal effects will be inconsequential.

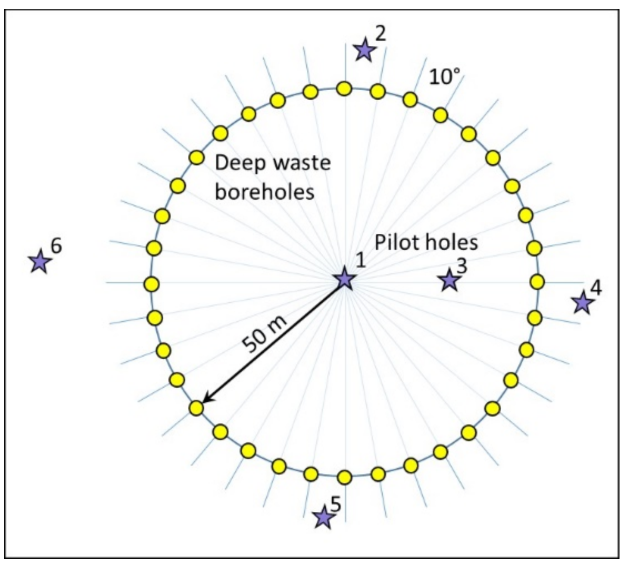


*Figure 4-1: Potential site layout for pilot hole locations*

For acquisition of data to aid in ranking the selected DBP repository sites, one initial central pilot hole is recommended, fully cored, with a core diameter of approximately 50-60 mm (e.g., the standard "NX" mineral exploration diamond core barrel provides a 54.7 mm diameter core). This size of core is adequate for most analyses, although large-diameter core may be needed later.

These pilot holes, after detailed characterization, will eventually become monitor boreholes. Standard diamond coring bits are shown in Figure 4-2.


*Figure 4-2: Diamond coring bits (Courtesy: Atlas Copco Ltd)*

The first pilot hole, labeled "1" in the figure, has as its primary function the more precise delineation of the geological and engineering characteristics of the repository. This first vertical pilot hole (Pilot Hole #1) should be drilled within the general layout of the DBP borehole array; Figure 4-1 shows it roughly in the centre of the array.

Pilot Hole #1 at each site might be drilled with a deviation angle of approximately 10-15° to intersect a greater number of natural fractures. Particularly in flat-lying sedimentary strata that have not been tectonically deformed, natural fractures tend to be close to vertical in attitude, so an inclined hole will intersect more fractures for measurements and testing. The decision to do a vertical or an inclined hole resides with the detailed engineering planners, and is based in part on the data collected by the geophysical and surface geological mapping exercise, combined in the GEM model.

Because any borehole in very dense, low-permeability strata must be considered in the long-term as a **potential pathway risk**, the final locations for the pilot boreholes should be chosen judiciously to restrict the probability of pathway development with the deep waste placement boreholes. In other words, an appropriate distancing criterion from the deep placement boreholes is necessary to minimize risks of pathway development. An argument can be made for keeping at least the shallow parts of pilot holes well outside the surface footprint of the borehole array. As a minimum, pilot hole offset criteria will be established as part of the pre-drilling site assessment process.

Measurements While Drilling (MWD) instrumentation should be employed on the diamond coring rig to capture real-time information about rate of penetration (ROP), fluid use (i.e. fluid losses), and other drilling parameters that can be used to better understand the subsurface and eventually guide the final design of the DBP repository borehole. As an example of MWD, if water or a drilling fluid is being used, precise metering of the drilling fluid entering the drill string and coming out the return flow line can identify zones of losses that may give indications relevant to fractured zone permeability or individual fracture conductivity (Sanfillippo *et al*., 1997).

In addition, information of borehole position and orientation should be logged to ensure all data collected during the testing program is appropriately georeferenced for the GEM to enhance the geological model developed from the geophysical and mapping programs. This data-rich GEM will eventually used to develop a safety case for the placement and construction of the drilled DBP boreholes and the overall design of the repository.

The results from Pilot Hole #1, when factored into the GEM, will lead to a decision to move forward, or to abandon the site because of geological unsuitability, or to suspend further activity pending results from other sites that are undergoing certification. Continued activity at the site entails advancing a number of additional pilot holes. The locations and attitudes of these holes are chosen on the basis of the GEM, enhanced by data from the first hole.

Pilot Hole #2 might be placed at a surface location well outside of the footprint of the placement boreholes at the surface, depending on the detailed characterization plan. These additional characterization boreholes may also be advanced at inclinations and in particular azimuth directions chosen to intersect steep natural fractures or fault-like features to help characterize the dispositions and distributions of the naturally existing fracture fabric. For rock mechanics testing, it may be advantageous in one of the pilot holes to obtain 100 mm diameter core specimens, and a decision to drill a larger diameter hole with selected sections of 100 mm diamond coring is probable.

Full characterization and utilization of the pilot holes as test holes, followed by instrumentation as monitoring boreholes, is recommended. The number of pilot holes needed for sufficient site qualification is a decision that depends on the findings from the previous stages, a classical adaptive management approach used to progressively reduce uncertainty. Again, it is recommended to limit the number of pilot holes because of a need to reduce the number of potential pathways that could develop over time.

Once the pilot hole program is sufficiently advanced at the chosen potential repository sites, the technical committee for site selection will make a ranking recommendation to the regulatory authorities. In turn, they will conduct appropriate hearings and commission expert third-party assessments, factoring in many layers of non-technical evaluation to arrive at a choice for the DBP repository.

Along with standard in-situ and laboratory tests for geological, geochemical, hydrogeological, and geomechanical aspects, corroboration and correlative relationships with the detailed downhole geophysical logs will be generated. Relationships of rock parameters with surface and cross-hole geological and geophysical approaches will be pursued. Recommendations for data to be collected can be widely found, such as published in the Canadian Nuclear Safety Commissions (CNSC) Guidance on Deep Geological Repository Site Characterization (2018). The pilot-hole testing program is based in part on Intera's (2008) Geological Characterization Program used to evaluate the suitability of a DGR in Bruce County, Ontario, Canada for low and intermediate level nuclear waste. The extensive work done in Canada for the granite batholith studies in Pinawa Manitoba (e.g., Davison *et al*. 1994) are also highly relevant, and must be studied in the context of any crystalline rock DBP repository concepts in Norway.

The following sections comprise a limited discussion of various testing activities in different geoscience domains that would be undertaken during the process of site qualification. This list is not exhaustive, nor is it weighted in favor of one aspect or another. It is recommended that the detailed test program be more rigorously specified and detailed in the pre-qualification assessment process, but that sufficient flexibility be incorporated to allow adjusting of the emphasis, depending on the findings (adaptive management). Also, different novel technologies may emerge that must be assessed in the context of making the safety case for the DBP repository.

### 4.4.1 Geological Testing

The geological program in a broad sense will consist of a quantitative combination and integration of core logging data, downhole geophysical log information, and detailed surface mapping. Before any site qualification involving drilling, a surface high-resolution seismic transect or 3D survey is required to delineate the large-scale features of the subsurface.

Once the site passes the first hurdle, at least the following geological histories and parameters are determined in this testing program:

- Structural geology, including a natural fracture occurrence and disposition model incorporating the evaluation of stress-relief sheeting fractures
- Stratigraphy (or divisions into GMU's – see below)
- Host rock type, fabric and mineralogical heterogeneity
- Fracture characteristics: frequency, orientation, cementation mineralogy, spacing, spatial predictability (heterogeneity), etc.
- History of glacial cycles in the past with estimates of erosion, stress cycling, and other relevant changes
- Natural resource potential within an exclusion zone radius chosen on the basis of social factors (part of the early mapping activity as well)
- Petrology assessment with quantitative lithology data for sediments
- Tectonic history, current tectonic setting, and potential for future tectonic activity

A visual core logging program using standard techniques along with high-resolution core photos and preservation of core samples following appropriate procedures should be followed. Core samples are preserved after recovery to allow access for subsequent testing and analysis programs. Depth-corrected borehole geophysical logs, downhole camera review, borehole radar, ultrasonic borehole wall scanning, and correlation to core features (discussed later) will supplement this core logging. The core logging data base is in its entirety recorded in the GEM that will guide further site qualification investigation.

An “Index Test” program for core examination using several standard methods is recommended. Index tests are “indicators” of mechanical behavior that can be easily done for great lengths of core at reasonable cost (Franklin and Dusseault, 1989, 1991). These data are often correlative in nature: the results can be correlated to rock properties such as elastic modulus, strength, permeability (particularly of interest in sedimentary rocks), porosity, state of weathering, and other measures relevant to rock mass assessment and engineering design. Index test data recorded along the length of a core (a “core log”) along with geological observations, fracture identification, and quick mineral identification, are used to correlate with the geophysical logs to allow empirical predictive models to be developed. The combination of core index tests and geophysical logging data, backed up by the geological and lithological interpretations, are used to define the GeoMechanical Units (GMU) in the repository rock mass.

A GMU is a rock mass unit that can be assumed to have approximately the same set of mechanical properties for further model development, and for inclusion as a distinct unit in the GEM. Given the statistical variation of all rock properties over many different scales, it is impossible to delineate precisely all rock properties at all locations. To render the problem tractable for site qualification and repository design, the rock mass is divided into a number of GMUs based on available data (e.g., Haug *et al*., 2007). The same approach is used in hydrogeological studies: based on porosity, permeability and other relevant properties, the rock mass is divided into HydroGeological Units (HGUs) that have approximately the same set of hydrogeological properties for flow system model development.

A partial list of “Index Tests” is included here. Most of them are non-destructive or used in a limited extent to allow preservation of intact core for other tests.

- RQD – Rock Quality Designation Index – evaluating the degree of natural fracturing of the rock mass through measurement of natural fracture frequency in core;
- Fracture Orientation – measurement of the angle and position on the core of each natural fracture (all cores are oriented to allow true fracture orientation calculations);
- Fracture Surface Classification – estimation of fracture roughness using standard images, presence of weathering evidence, clay or other debris; fracture natural cementing materials, etc.;
- Point Load Test – carried out on pieces of core to correlate to the intact rock strength (tensile and compressive strengths) through standard charts;
- Acoustic Wave Velocities – carried out across intact core sections, or longitudinally on specimens prepared for Unconfined Compressive Strength (UCS) tests, using ultrasonic devices;

- Schmidt Hammer Tests (or other similar devices) – an empirical measure of the rock elastic modulus, also correlated to the UCS values, non-destructive, can use along entire core length;
- Scratch Tests – usually carried out on slabbed core in the oil industry, values are correlated to the UCS value (i.e. strength), usually limited to sedimentary rocks;
- Brinell Hardness Test – a modified metallurgical Brinell Hardness with measurement of load versus penetration depth, usually for sedimentary rocks, correlated to strength and stiffness;
- Cherchar Abrasivity index test or Los Angeles Abrasion Test to analyze the cuttability of the host rock for wear on drilling machinery;
- Slake-Durability tests or other tests to assess any tendency for significant attrition or degradation of the rock from exposure to water;
- Unconfined Compressive Strength (UCS) Test – a destructive compressive strength test carried out on prepared flat-cut-end core cylinders with length of twice the diameter. All UCS specimens (including cut-off end pieces) are subjected to other appropriate Index Tests before compression. The broken UCS rock is photographed, "reassembled" with masking tape, and returned to the core box.

There are several rock mass classification systems for mining engineering, tunnelling and slope stability engineering (Cai and Kaiser, 2005). The data collected will be used to generate rock classifications in all common rock mass classification systems for comparison and consistency. Several typical Index Tests performed on core or cored rock fragments are shown in Figure 4-3.

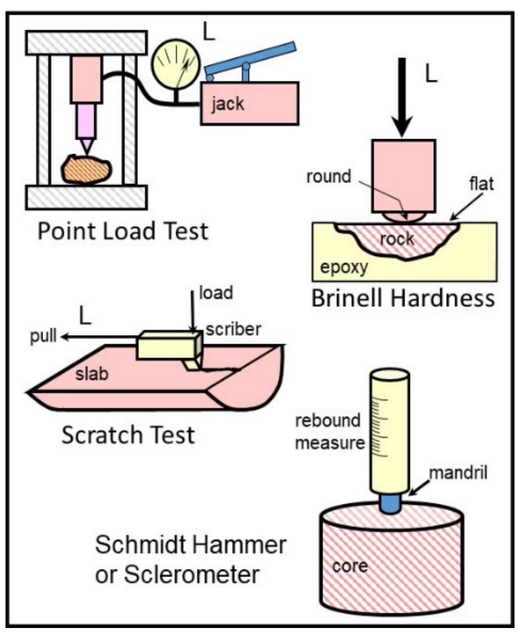


*Figure 4-3: Common Index Tests Used During Core Logging*

### 4.4.2 Hydrogeological Testing

A suite of in-situ (e.g., pilot-hole packer flow tests) and laboratory testing programs (e.g., axial permeability measurements) will be paired to characterize the hydrogeological features of the host rock and overburden. As there is the possibility of siting a repository in sedimentary rocks with appropriate properties, or in igneous rocks where flow is dominated by fractures, different hydrogeological approaches will have to be considered for different sites chosen. It may even transpire that the final canister placement takes place in crystalline rock underlying a cover of several hundred meters of dense sedimentary strata (Figure 4-4). If the fluid flow potential of the rock unit is dominated by fracture flow, different approaches are needed compared to rocks dominated by matrix flow.

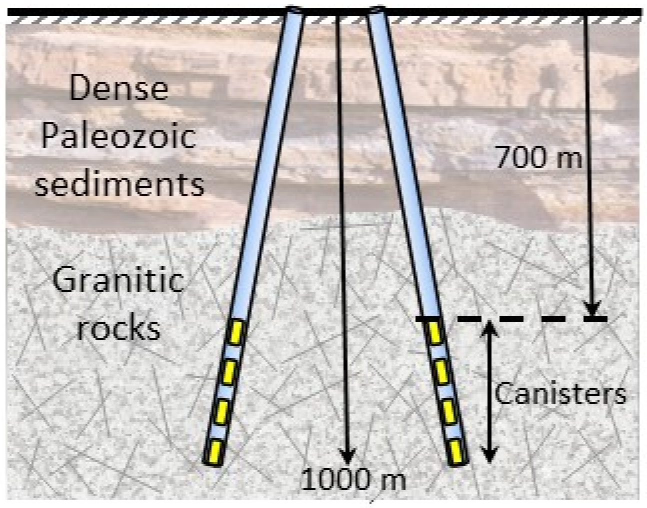


*Figure 4-4: Possible geological scenario for deep borehole placement of wastes*

The following macro-scale hydrogeological regime characteristics are recommended for delineation, along with specific parameters determined at a small (laboratory) scale, backed up by geophysical log measurements (estimates) of porosity and permeability, if appropriate:

- Definition of the regional scale hydrogeological regime for the repository, including regional recharge and discharge sites, specific flow units (aquitards and aquifers), and general aspects;
- Regional and site-specific groundwater flow conditions expressed in terms of head for all permeable flow units;
- Flow rate for aquifer flow units or for individual fracture planes, as appropriate;
- Direction of flow, as determined by the three-dimensional head mapping, or, if possible, by flux measurements in individual conductive fractures;
- Hydrogeology of major rock units in terms of anisotropy, layering, and other characteristics at the macro-scale (i.e., specifying and quantifying the Hydrogeological Units – HGUs);

- On-site hydrogeochemical assessment of any groundwater that flows into the borehole during drilling to reconstruct the general groundwater geochemistry within the fracture(s) in terms of its acid-base (pH, alkalinity), redox and, by laboratory measurement, ionic composition;
- Porosity of the various HGUs (more relevant for sedimentary rocks, less so for competent and lightly fractured crystalline rock masses);
- Hydraulic conductivity measurements for rocks and joints, with field testing for joints and fractured zones in the case of crystalline rocks and fractured tight sedimentary rocks, backed up with permeability tests on core specimens for sedimentary rocks;
- Fluid density measurements with depth (salinity can be used as a proxy) for assessment of regional flow stability; and (but not exclusively),
- Delineation of pressure gradients across aquitards to ensure their effectiveness as flow barriers.

Based on other hydrogeological characterization programs, the following more specific in-situ and laboratory-based tests may be conducted in various combinations in various pilot holes to appropriately determine the hydrogeological conditions:

- Tracer placement during drilling: placing tracer materials within the drilling fluid (e.g., organic dye or boron salts) to evaluate flow of drilling fluid from the borehole at different points in the drilling process; for example, after drilling, the pilot hole can be packer tested with drawdown conditions to measure how much tracer returns to a critical section of borehole over a time period;
- Tracer tests in single boreholes (injection and flowback with measurements of tracer adsorption within the fractures) and between boreholes;
- Direct borehole hydraulic testing using straddle packer equipment to isolate a region of the borehole to conduct various flow tests on hydrogeological units, fractured zones, or individual fractures. Tests could include slug tests, drill stem tests, drawdown tests and pulse tests, depending on the hydraulic conductivity of the isolated rock unit;
- Formation pressures and hydraulic heads should be measured and monitored over time in at least one pilot hole through installation, after hydraulic testing, of a multilevel piezometric well with the potential to obtain small fluid samples periodically from behind the casing (i.e., Westbay technology)[36];
- Petrophysical property analysis in the laboratory using mercury injection (or helium) porosimetry, porosity and fluid saturations, and brine and gas pulse permeability for sedimentary rocks.

[36] https://www.westbay.com/

These tests can be paired with the geophysical data collected from the array of geophysical logs to establish useful correlations to help interpolate between boreholes and establish a hydrogeological model based on HGUs as part of the GEM.

### 4.4.3 Geochemical Testing

A suite of laboratory geochemical tests paired with the data from the geophysics logging program is established to determine the geochemical composition of the host rock, overburden, and pore or fracture water. Recommended geochemical information to be collected is listed below:

- Mineralogical composition, including petrographic analysis, of all fracture fillings and materials;
- General determination of the groundwater/fracture water geochemistry in terms of species and concentrations of ions and cations with depth;
- Stable and radioactive isotopic fingerprinting of the water in the rock mass with depth to determine its age, mixing history and long-term (historical – post glacial) flow patterns;
- Effective diffusion rates of radionuclides, particularly cations, in the rock mass, based on diffusion testing;
- Solubility, speciation and retardation coefficients of various radionuclides that could enter fractures within the rock mass;
- Groundwater corrosivity towards engineered barriers, including canister barriers, and installed adsorptive and low permeability barriers used to seal the placement boreholes;
- Potential for gas generation from the interaction of the waste material with other materials in the engineered barrier system;
- Diffusive property estimates: X-ray radiography and through-going diffusion methods can be used at the laboratory scale to get effective diffusion coefficients and rock absorptivity capacity factors; and (but not exclusively),
- Water-rock interaction assessments.

Based on the work completed by other programs to evaluate geochemistry for other nuclear waste repositories, a combination of the following tests should be used to evaluate the geochemical nature of the environment, and compare it to existing databases from public sources:

- Lab Petrography, mineralogy and geochemical testing of core: mineralogy (optical microscopy and XRD), geochemistry (Fusion ICP-optical emission spectrometry, ICP-mass spectrometry), cation exchange (Cation Exchange Capacity) of fracture infill minerals, pore structure (scanning electron microscope image analysis, and numerical models for simulation diffusion and exchange processes for pairing with appropriate macroscopic petrophysical test results).
- Pore fluid geochemistry: sample groundwater for testing from borehole straddle packer work, preserving gas content; crush and leach rock samples for cation exchange capacity

testing, solubility, and other measures. Test pore fluids and gas samples (vacuum extraction) for stable isotope concentrations for age assessment (glacial or other origin), mixing behavior in the rock mass, differentiation of fluids with depth, diffusion rates, and radioisotopic analysis for age assessment using $^{14}C$, $^{3}H$, etc.

Sampling techniques will need to be evaluated to ensure limited contamination of formation waters by drilling fluids that might impact the geochemical testing program. Double packer production tests are recommended with continuous sampling to test for drilling fluid penetration depth as well as to sample the in-situ water for geochemical characterization.

#### 4.4.4 Geomechanical Logging and Testing of Core

The thermomechanical and mechanical properties of the rock mass must be delineated in detail, and the data stored in the GEM to create a model to serve as the basis for mathematical modeling of borehole stability, mechanical interactions, stress changes and thermal stress-strain effects in the rock mass. Assuming that the rock mass is divided into a reasonable number of GMUs, a suite of in-situ and laboratory testing paired with the geophysics program can be used to determine the three-dimensional disposition of the geomechanical characteristics of the host rock and overburden GMUs. A recommended list of geomechanical properties to evaluate for each GMU would include:

- The magnitude and orientation of the in-situ stresses as a function of depth in the repository, as well as a sufficient number of measurements to allow study of the statistical reliability of stress measurements. Some of the methods that should be included are:
    - Overcoring measurements with depth in one or more pilot holes;
    - Inversion of high-precision multi-arm caliper data that provide information on borehole ellipticity.
    - Examination of the pilot hole walls (and later, the guide hole and the large diameter borehole walls) for evidence of spalling or breakouts from which stress orientations and relative magnitudes can be inferred;
    - Assessing whether anisotropy in acoustic velocities are correlated with stress anisotropy to infer orientations and relative magnitudes;
    - Hydraulic fracturing tests for minimum principal stress measurements may or may not be done, depending on the concern for the creation of potential pathways in the rock mass.
        - An option is to do only hydraulic fracture stress measurements in a more distant exploratory (characterization) borehole that is still part of the relevant repository rock mass, but sufficiently offset so that the pathway generation risk is negligible.
        - An option is to perform hydraulic fracturing tests of small volumes only, and sparingly.

- The stress-strain properties of the intact rock, the fractures, and the rock mass at various scales are evaluated using laboratory and borehole tests, including:
    - Triaxial testing of cores (scale of 5 cm and perhaps 10 cm) from selected rock units, with a designed test protocol to evaluate loading modulus, unloading modulus, elastic behavior, permanent strain behavior, with simultaneous measurement of acoustic velocities under stress;
    - Testing at different orientations to inherent gneissocity or bedding to evaluate anisotropy of deformation properties;
    - Thermal properties under stressed conditions (thermoelastic coefficients, thermal conductivity);
    - Borehole pressure-meter tests using a high-pressure device so that radial strain can be measured upon a change of radial load (scale of one metre) in a sufficient rock volume to aid in properties upscaling;
    - Estimates of the intact (in-situ) compressibility of natural fractures in the rock mass using various techniques (pressurization while measuring flow to estimate aperture changes is one way, image analysis and model development for mathematical simulations is another);
    - Developing a macroscopic deformability model by integrating the deformability (stiffness) estimates at different scales.
- The strength properties of the intact rock and the natural fractures should be measured or estimated through appropriate testing procedures:
    - Triaxial testing of cores from selected rock units, with a designed test protocol to estimate strength of the rock under low confinement conditions (borehole wall vicinity), to be combined with the Unconfined Compression Strength values to give a consistent strength model;
    - More important may be estimation of the shear strength of discontinuities (though this may be impossible in-situ because of the constraints), using core samples, image analysis of surface roughness, and model development.
- The influence of time, temperature, scale, anisotropy, pore fluid pressure and other relevant factors that may impact long-term stress-strain-strength properties.

Using the work completed by other nuclear waste repository programs to evaluate geomechanical response of the host rock, a comparative assessment should be made with the data available to identify possible areas of concern or areas where more information is needed.

#### 4.4.5 Borehole Imaging (Televiewer and Ultrasonic Scanner)

The entire drilled length of each pilot hole (and perhaps also the guide holes for later borehole development) will be imaged, scanned, and measured to allow for visual confirmation of the in-situ and laboratory test results and to aid in the QA/QC program. Table 4-3 provides a list of downhole imaging techniques and the associated target information that can be acquired with each technique.

*Table 4-3: Summary of downhole imagining techniques*

| **Downhole Imaging** | **Geoscience Data Need Discipline** | **Target Information** |
|---|---|---|
| Multi-Arm Caliper | Geological<br>Geomechanical | Borehole Diameter, Zones of Instability, Stress Analysis |
| Acoustic Televiewer | Geological<br>Geomechanical | Borehole Diameter and Orientation,<br>Fracture Occurrence and Orientation,<br>Borehole Breakouts |
| Video Televiewer | Geological<br>Hydrogeological | Stratigraphy, Discontinuities, Borehole Wall Geometry, Flowing Zones, Gas |
| Ultrasonic Scanner | Geomechanical | Borehole Deformation Analysis for Stresses, Fracture Traces and Aperture in the Wall |

### 4.4.6 Borehole Geophysics including Cross-Hole Acoustic Tomography

After completion of each pilot hole, a suite of geophysical tests will be completed downhole to aid in the programs for the geological, hydrogeological, geochemical, and geomechanical programs. This will allow for continuous logging of the entire pilot hole to aid in generation of the GEM. Table 4-4 lists borehole geophysical tests and the information that can be gathered using logging techniques.  This list is not exhaustive, there exist other geophysical or wireline tools that can measure different properties.

*Table 4-4: Summary of geophysical logging techniques*

| **Borehole Geophysical Log** | **Geoscience Data Need Discipline** | **Target Information** |
|---|---|---|
| Gamma/Spectral Gamma | Geological, Geochemical | Lithology, Stratigraphy |
| Gamma-Gamma (density) | Geological, Geomechanical | Lithology, Stratigraphy, Density |
| Neutron | Geological<br>Hydrogeological | Lithology, Stratigraphy, Rock Porosity |
| Resistivity/Conductivity | Geological<br>Hydrogeological | Lithology, Stratigraphy, Salinity of Pore Fluids |
| Sonic/Full Wave Form Sonic, Multi-Receiver Sonic Log | Geological<br>Geomechanical | Lithology, Stratigraphy, Structure, Bulk Modulus, Rock Competence, Sonic Velocity |

| | | |
|---|---|---|
| Downhole Geophones for Vertical Seismic Profiling | Geological, Geomechanical | Stratigraphy, Structure, Rock Mechanical Properties |
| Temperature Profile | Hydrogeological | Relative Inflow and Thermal Anomalies, Porosity, Thermal Diffusivity |
| Fluid Resistivity | Hydrogeological | Groundwater Salinity, Vertical Water Movement in Borehole |
| Magnetic Resonance | Hydrogeological, Geochemical | Nature of the Free, Crystalline, and Adsorbed Water in the Near-Borehole Vicinity |
| High Precision Multi-Arm Caliper | Geomechanical, Stresses | Breakouts Development, Ellipticity Modeling for Stresses |
| Gravimeter Log | Geomechanical | Precision Density Profiling of the Rock Mass |

Cross-hole seismic methods, vertical seismic profiling, and similar methods can be used to develop a more precise geophysical model from the pilot holes, and also, when the site is being drilled, through use of each of the guide holes, if deemed necessary (Doetsch *et al*., 2020). Different approaches to seismic surveys of various levels of detail are sketched in Figure 4-5.

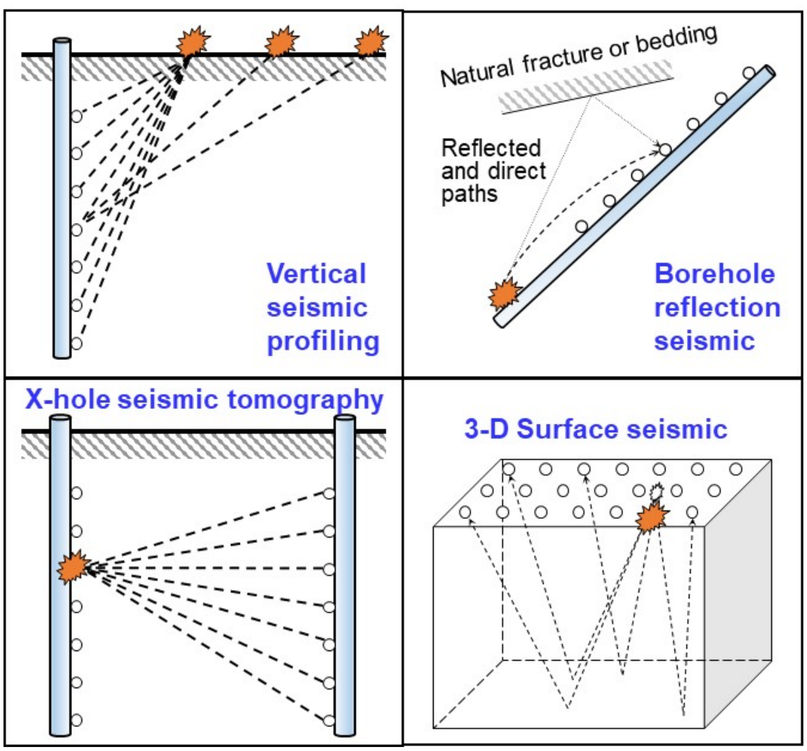


*Figure 4-5: Seismic methods to characterize the acoustic character and structure of the rock mass*

Electromagnetic tomography can also be used in cross-hole configurations, and all of these methods, including seismic methods, are generally better if done in uncased holes with good sensor coupling to the hole wall.

### 4.4.7 Other Site Qualification Measurements and Instrumentation

A repository site will be subjected to additional measurements and monitoring strategies, other than the ones listed above. In particular, several are listed here, and this list is not exhaustive:

- Seismic monitoring and hazard assessment requires boreholes with geophones and accelerometers to measure natural and induced microseismic events. This local seismological network will be in use throughout the construction phase and beyond the completion and closure of the repository. The local network is integrated with the national seismological network.
- Pilot holes will be converted to instrumented boreholes that may include various types of instrumentation: potentially, measurements of deformation, fluid pressure and chemistry, and temperature fields.

## 4.5 Additional Site Qualification Assessments

Additional characterization of the surface environment will likely be required by the regulator. Further surface process evaluations including natural hazard risks should be implemented to ensure that changes to surface conditions have no impact on the waste management system ability to function safely for long times. These surface factors include:

- Climate (temperature, precipitation, rainfall, snowfall, evapotranspiration etc.), with a strong focus on extreme events and any possible interactions with the deep waste placement sites, and with a view to issues that could arise from extended climate change impacts;
- Aquatic and terrestrial environment and ecology, focusing on impacts on protected species, on special ecosystems, and on surrounding systems that the site could affect;
- Topography, surface hydrology, flooding, and other factors or changes that may alter the pathway of fluids on the surface and how this could impact the deep subsurface;
- Geomorphology, or the distribution of landforms, assessing the probabilities of debris slides or avalanches and potential impacts;
- Complete geotechnical characterization of shallow surface deposits (typically glacial , organic, or fluviolacustrine deposits of Recent age, often called “surficial deposits”) including soil type and distribution, mechanical parameters, hydrogeological parameters, and any potential impacts of the presence of these surficial deposits on the operation and post-closure response of the rock mass.

## 4.6 Summary

Prior to confirming the location of the site for the DBP repository and construction of the DBP borehole array, a detailed site qualification process will be undertaken. This site qualification process will involve first the development of a list of candidate sites and ranking them based on a set of parameters. A shortlist will be generated based on an increasingly rigorous examination of various parameters that narrows the number of candidate sites until only several sites (2-4?) emerge as the leading candidates.

These remaining sites then go through further but still preliminary surface geological and geophysical mapping exercises, followed by pilot hole exploratory drilling, to develop a Geological Engineering Model of each site to a sufficient level that allows a final ranking of site suitability on technical grounds. Various means of determining properties and subsurface conditions are implemented throughout the site qualification process. This will be undertaken in an Adaptive Management framework (e.g., Williams *et al*., 2012) so that a continuous decision-making and action modification process takes place, folding all new data into the digital GEM information base and re-evaluating site suitability regularly. From these programs, the increasing quality of the assessment of the suitability of the site geology, geochemical, hydrogeological and geomechanical parameters and properties for repository placement results in a clear preferential ranking of the candidate sites. This ranking then allows the inclusion of other factors of a non-technical nature in order to make a final site choice.

For example, initially a pilot hole program should be stipulated at all short-list candidate sites to allow for building a detailed GEM. The first pilot hole will be drilled in the same general location as the potential future DBP borehole array construction. The initial pilot borehole will allow for sufficient in-situ and laboratory testing to permit the re-assessment of the various sites, which may lead to disqualification of one or more sites. The data management system involved in the GEM has capability to ensure integrity of information and data generated with appropriate QA/QC programs in place. This allows the GEM to be regularly updated so that the expert advisors can continue the process of suitability evaluation for the remaining sites. It is recommended that throughout the process, estimates of uncertainty be undertaken so that probabilistic risk assessments can be executed regularly.

During the site qualification phase, which will involve more pilot holes and various tests, the selection of a preferred candidate site for the DBP concept will emerge. At this single site, the continuation of the qualification process leads to a highly detailed GEM used to develop a safety case for the DBP concept and structural design of the borehole systems. Other sites are not subjected to the detailed qualification process unless discoveries at the chosen final site lead to a degradation in its suitability assessment. Once fully qualified, the pre-design and design of the repository is based on the use of the GEM, which is continuously updated and refined during the course of the construction of the repository and the placement of wastes, until the repository undergoes closure activity at the surface.

# Chapter 5: Commercial Drilling

## 5.1 Overview of Commercial Drilling

The stipulation of drilling equipment type and capacity depends on the final choices for the DBP repository design, and this can only be made once canister geometry is specified, once the buffer and barrier design and placement have been determined, and once the specifics of the repository geometry are chosen. In this report, a scenario of a one-kilometre deep borehole is used for discussion. The choice of depth depends on the hydrogeological characteristics of the site and the perceived and calculated security against leakage provided by the array of barriers. These will not be finalized until after the pilot hole exploration, with associated measurements and in-situ testing, is completed and analyzed by the experts involved and the repository technical committee. Then, selection of large-diameter drilling equipment capabilities can be undertaken.

We recommend that the guide hole and large-diameter borehole drilling activity be completed before placement of waste. Placement operations will take place with different equipment – wireline and coiled tubing technologies – and likely be semi-automated and in part remote controlled.

The commercial deep drilling industry (> 1 km) possesses a wide range of technical capabilities and equipment geared to the needs of two main sectors (mining and O&G – oil and gas). These capabilities have been developed, tested, and utilized in the O&G industry and the mining industry for many decades, and the technologies are highly advanced. There have also been developments in the high-temperature geothermal energy sector, where drilling into high-pressure dry steam reservoirs presents similar challenges. A specific aspect of the site qualification for the DBP repository is the identification of locations where there are no exceptional conditions such as abnormal (strongly artesian) water pressure[37], lost circulation potential, presence of oil or gas, unusually high temperature gradients, in-situ stresses that are near a fault-slip critical condition, or complex structural features (folds, major faults…). This means that the qualified DBP repository site will be considered geologically routine for experienced commercial drillers. Furthermore, the site conditions will not require geothermal drilling expertise, thus the special capabilities of geothermal drilling systems will not be further discussed.

The equipment and practices developed in the mining and O&G sectors are fully transferable to the construction of a deep borehole array for the placement of high-level radioactive waste. The construction of a DBP repository can be completed with existing mature drilling technology that is well known to the industry sector (mining or O&G), thus providing limited potential for problems and emerging risks during the construction phase. The DBP repository technical

[37] By limiting siting to recharge zones, abnormal pressures of any kind are unlikely in crystalline rock masses.

committee may choose to impose additional constraints and quality assurance measures on the drilling program if it is deemed appropriate, such as intermediate trips[38] during drilling to inspect the borehole wall, overcoring stress measurements during pilot hole advance to evaluate stress state, restrictions on penetration rate and bottom-hole pressures, and so on.

The three distinct drilling phases encountered in the repository qualification and development are certain to use different types of equipment:

- Pilot hole drilling to obtain the necessary site qualification information, develop the Geological Engineering Model, and install monitoring equipment;
- Assuming that the site qualifications are satisfied, then guide-hole directional drilling to establish the pathway for each deep waste placement borehole, also used to fully evaluate the placement borehole conditions and add to the site model.
- Deep large-diameter borehole development following the guide holes to generate the appropriate placement conditions and isolation strategies at depth.

This section will provide a short review of commercially available drilling technologies, tools, and drilling companies. First, a review of tools to construct the deep borehole is provided. Depending on the orientation of the borehole (i.e., vertical, sub-vertical, deviated) the tooling requirements will differ, but for the DBP repository, a limited deviation from vertical is advised to facilitate placement of waste canisters, therefore boreholes with large deviations (>10-12°) are not discussed.

It is our professional opinion that current technology available in the drilling industries (mining, O&G) is entirely adequate to perform the full range of exploratory functions (deep hard rock coring, deep small diameter percussion drilling) and deep borehole creation functions for the proposed high-level waste repository. For these functions, no remote control or robotic activity is needed, and conventional equipment and experienced personnel are widely available.

Furthermore, we assume that the process of drilling and preparing the large diameter boreholes for canister placement is fully decoupled from the process of waste placement. Once drilling is complete, we assume that the drilling equipment will be released, and specialized wireline, coiled tubing, and buffer placement equipment will become active on site. These placement activities are likely to be partially robotic, and very likely to be partially remote controlled, particularly in the handling of the canisters.

[38] A "trip" is the drilling term describing removing the entire borehole drilling assembly to change the bit and return to drilling, or to perform exceptional functions such as placing casing, examining the borehole for physical properties, taking special core, etc.

## 5.2 Commercial Drilling Equipment – Large Diameter Borehole

The following section provides an overview of commercial drilling equipment that may be utilized during the construction of a large-diameter (≈600 mm) deep borehole. This is the key aspect of the drilling program for the DBP repository: creation of high-quality deep, large-diameter boreholes into dense rocks such as granites, gneisses, or highly indurated sedimentary rocks of low porosity.

The ultimate design of the deep borehole repository is not finalized and will not be finalized until the construction phase begins, long after site qualification and study. Different drilling techniques and technologies can be considered during the site qualification and design process; the choice depends on the final profile of the deep borehole placement and isolation system as determined by the DBP technical committee and advising experts. Currently, the main repository variables to be stipulated, with the probable range of values, are:

- Depth of conductor pipe (5-25 m deep)
- Depth of surface casing shoe (200-500 m deep)
- Depth of emplacement borehole (1 km is the current scenario, may be 1-3 km)
- Diameter of emplacement borehole (≈500-750 mm, depends on canister dimensions, buffer zone requirements)
- Number of deep boreholes (10-36, depends on canister numbers, dimensions, spacing, depth…)

These criteria can be met by O&G industry drilling capabilities, or by mining industry drilling capabilities. Hence, this review addresses equipment available in both industries. Nevertheless, the proposed rock conditions (strong brittle rock masses with low porosity and few natural fractures), hydrogeological conditions (no artesian pressures, no oil or gas) and the desired site characteristics (reasonably compact surface array of deep boreholes) tend to significantly favor the choice of a mining equipment scenario.

The terminology for oil and gas activities is arcane and can be misunderstood. It is recommended that the following industry glossary be accessed for clarification.[39] The general information site called PetroWiki[40], maintained and made available through the Society for Petroleum Engineers (SPE), is a useful source of general information on all aspects of the O&G industry. More specific information is widely available on commercial and academic sites.

[39] https://www.glossary.oilfield.slb.com/

[40] https://petrowiki.org/PetroWiki

Mining industry glossaries are also necessary once delving into the mining literature, and these are available through government[41, 42] and commercial service sites.[43]

For specifications, equipment and capabilities, it is necessary to examine specific commercial providers or to employ the services of an experienced mining or O&G drilling engineer.

### 5.2.1 Drill Rigs

A drilling system, commonly called a "drill rig", consists of a set of equipment and machinery used by the operator to construct a well. The drill rig system[44] is comprised of various elements, the most important equipment sub-systems are the hoist system, power system, circulating system, rotating system, and the blowout prevention system used if high fluid pressures or hydrocarbons are to be encountered. These systems work in conjunction with each other to complete the safe construction of the drilled borehole. Specific consideration of drilling equipment is made with respect to the different requirements for exploration boreholes, guide holes, and construction of an array of deep, large diameter boreholes for waste placement.

There are two classes of large rigs that might be used – truck-mounted drilling rigs or solid foundation rigs that can be skidded or rail-tracked to a different hole location a short distance away (5-50 m).

The hoist system allows for the handling of drilling materials (drill bit, drill pipe, casings) at the surface, drilling, and the lifting of materials (the "drill string") from inside the deep borehole ("tripping") in order to change the drilling apparatus or drill bit, to place casing, or to conduct other activities. The hoist system consists of the derrick and mast along with hoist, crown block, traveling block, and any substructure required to support these components. The hoisting system for most conventional O&G drilling rigs is a steel-wire cable draw works, although some new designs of O&G rigs include hydraulic elevator traveling blocks instead of steel cable draw works. In the mining industry, hydraulic masts are common, and cable-hoist masts are perhaps less common than in the O&G industry.

The hoist system for a large-diameter deep borehole scenario requires a significant lifting capacity due to the weight of the drill string and casing. This is because the combination of overall depth of construction and diameter of the bore necessitates larger/heavier equipment. The lifting capacity of commercially available drill rigs is sufficient for the loads to be carried during construction of a deep borehole. Commercially available large rigs with hook loads of 900 metric

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[41] https://www.sec.gov/Archives/edgar/data/1165780/000116578003000001/glossary.htm

[42] https://www.aadnc-aandc.gc.ca/eng/1100100028056/1100100028058

[43] https://www.angloamerican.com/futuresmart/stories/our-industry/mining-explained/mining-terms-explained-a-to-z

[44] Excellent labeled diagrams are widely available on search engine sites.

tonnes and setback capacities of 454 metric tonnes exist on the market (e.g., DRILLMEC[45]). These are capable of drilling to depths exceeding 8 km.

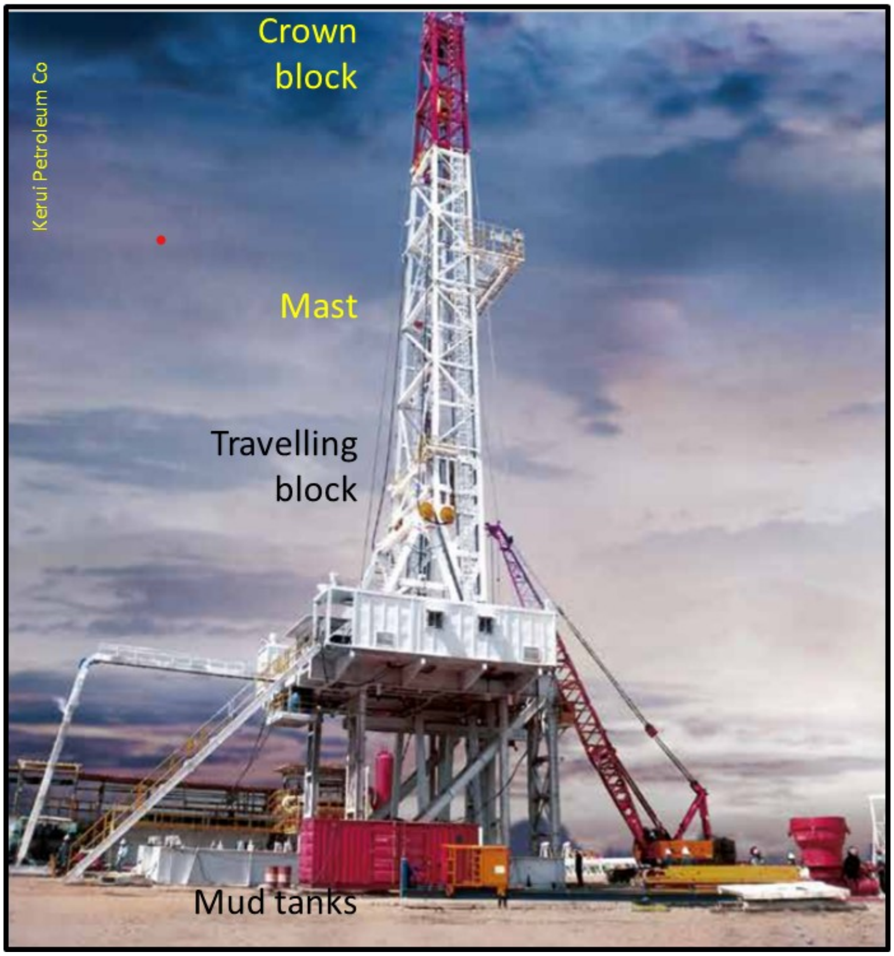


*Figure 5-1: Standard modern oil and gas drilling rig (Courtesy: Kerui Petroleum Co.)*

In the mining industry, systems capable of drilling large-diameter boreholes to depths of several km are available because of the need for ventilation or escape shaft drilling (e.g. Schramm[46]). Drilling from the surface in the mining industry is referred to as “blind drilling”, and equipment to drill 600-800 mm diameter boreholes in hard rock is widely available.

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[45] http://www.drillmec.com/en/p/drawworks-gds-gdm-series/

[46] http://www.schramminc.com/


*Figure 5-2: Large-diameter borehole (28 inches, 710 mm) rock drilling rig (Courtesy: Schramm)*

The rotating system for a conventional (pre-1980) drilling rig allows the rotation of the drill string with a gear- or chain-driven rotary table, with which the kelly and the swivel are integrated to allow fluid circulation down the drill pipe. However, in modern rigs, these components' functions are grouped together as a top-drive system where the swivel is also a hydraulically powered rotation device. Like the lifting capacity of the hoist assembly, the rotary system will require a high torque capability to rotate a heavy drill string in high strength rocks.

Commercially available rotating systems can provide the required torques, especially for heavy-duty drill rigs with high lifting capacities to advance a large-diameter borehole to considerable depth. In the drilling of a DBP repository, the rig must drill the surface casing hole to a depth of +200 m; to accommodate the drilling of an emplacement borehole of 600 mm (assumed), the surface casing borehole will have to 750-800 mm diameter. This means that the drilling rig floor design is expected to accept +800 mm (≈32 inch) diameter drill string assemblies; depending on choices of drilling technology, drill collars for additional weight-on-bit and double walled drill pipe will add to the hoist load.

Downhole drilling turbines ("mud motors") actuated by the drilling fluid are commonplace for deep O&G drilling, although for the large diameter surface holes conventional drilling is used. In the mining industry, downhole hydraulic (air or water) percussion hammers ("hammer drilling") actuated by the drilling fluid have in part displaced conventional rotary drilling for large diameter boreholes. In the O&G industry, large-diameter holes (>400 mm) are used for the upper part of deep boreholes, and usually are being drilled through soft rocks (higher porosity shales and sandstones), not granites, so they are seldom drilled with down-hole mud motors; rather, rotary drilling is used.

The circulation system allows for drilling fluid to flow from the surface to the bottom of the borehole and then subsequently back to the surface, carrying the cuttings, and in the case of percussion drilling or downhole mud pumps, also providing the driving rotary action or the percussion action for rock penetration. The fluids used depends on the drilling technology employed, the rock types, the subsurface pressures expected, and other parameters (see Chapter 1). The circulation system consists of compressors or pumps, mixing systems, distribution lines and accumulation systems (tanks) to remove cuttings and condition the drilling fluid. Conventional circulation systems involve the fluid following down to the bottom of the borehole through the centre of the drill pipe, then returning to the surface through the borehole annulus (between the drill sting and the borehole wall).

Reverse circulation systems also are used, especially in drilling large diameter boreholes in the mining industry, where the velocity of the fluid returning in the large diameter annulus will be insufficient to bring the cuttings to surface. Reverse circulation is done in two ways: the first involves keeping drilling fluid in the annulus and lifting the fluid up through the centre of the drill pipe (perhaps with air lift methods). The second involves using concentric double-wall drill pipe where the fluid is pumped down and returns through the annulus between the two concentric walls, or through the inner annulus, depending on the design. This is needed if the fluid is powering the downhole hammer in a large diameter case where the velocity is insufficient to clear the exterior annulus. In the latter case, the exterior annulus may or may not be maintained with a significant fluid level, depending on rock integrity and drilling strategy. Figure 5-3 shows a configuration of double-wall drill pipe for air hammer drilling where the air is actuating the hammer and returning the cuttings to surface through the inner annulus.

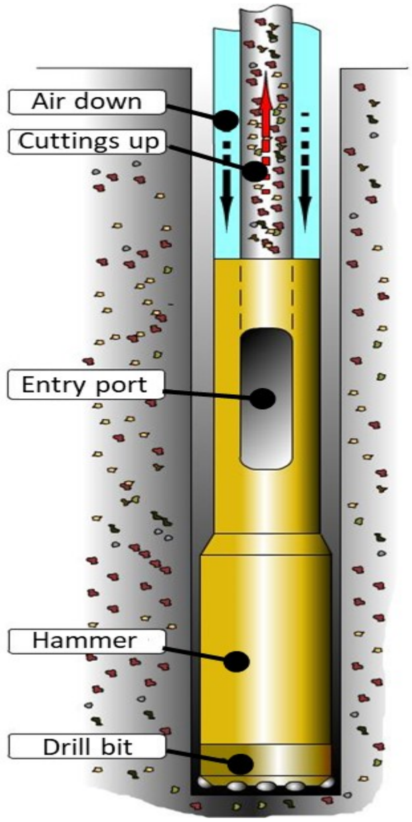


*Figure 5-3: Air Hammer Reverse Circulation Drilling*

The simplest reverse circulation systems have the drilling fluids flow down the annulus of the borehole and then up through the drill string. Reverse circulation allows for more rapid flow of cuttings to the surface for given flow rates due to the smaller cross-sectional area of the drill string compared to the borehole. However, hazards could include materials being stuck in the drill string that would not occur during normal circulation. Both methods are technically feasible and offered by many drilling services companies. The circulation system utilized during construction of the DBP repository must utilize pumps and circulation systems that can exert the required pressure at the appropriate rates to circulate a fluid column of that may be several kilometers in depth with a diameter up to 600-800 mm.

*Figure 5-4: Deep geothermal EGS drilling rig being set-up in Cornwall, England (Courtesy: thinkgeoenergy.com)*

Direct drive, electrical power or a power generation system is used to run all the other drill rig systems. In remote locations, this is usually provided by diesel or diesel-electric engines, but access to local grid connectivity gives the possibility for use of an all-electric drilling system. Exceptionally, it is possible to use natural gas turbines to provide the electrical power for an electrical rig. The power generation system must be able to generate enough power for all the sub-systems with the increased demands placed on them because of the depth and the diameter of the deep borehole, and under the worst conditions foreseen. Any large capacity rig is equipped with the appropriate power generation system.

The blowout prevention and wellhead systems are safety equipment assemblages that use valves to allow the borehole to be drilled, while giving the capacity to suddenly shut the well in control and safely manage any pressures that are encountered at depth that exceed the hydrostatic pressure of the column of fluid in the borehole (see Chapter 1). For the DBP repository, the blowout preventers (BOPs) are large valves attached to the cemented-in-place 200-300 m deep surface casing during drilling that can fully shut the well in case of emergency associated with encountering elevated pressures. BOPs may be required as a safety feature in constructing the DBP repository boreholes; however, it is unlikely that the dense rock formations that drilling will advance through will pose issues with high pressures as this will likely preclude them from being selected as a suitable site. Furthermore, with depth in crystalline rock or high-density sedimentary rocks, the natural fractures are under a high confining stress and are often essentially closed, so that flow is constrained to extremely low rates. For these reasons, it is often possible to drill down to considerable depths in such rocks without blowout concern, and deep diamond drilling exploratory holes in hard rock areas can penetrate several kilometers deep without borehole pressure control concerns.

BOP components are standard safety components of both the geothermal and the oil and gas drilling industries but are unlikely to be used in the development of a DBP repository that meets the suggested qualification requirements.

### 5.2.2 Drill Strings

The drill string is an assembly of pipe extending from the surface of the bottom of the borehole. The drill strings allow for the drill bit to be extended to the bottom of the hole while transmitting the vertical and rotational forces loads to allow it to drill, and to actuate downhole motors for rotary drilling or downhole hammers for percussion drilling. In normal circulation systems, the drill string also is a conduit for the drilling mud to move from the surface to the bottom of the borehole. As mentioned above, for special reverse circulation systems, double-wall drill pipe may be used when it is also necessary to provide the actuating power and return the cuttings inside the drill pipe. The drill string also guides and controls the trajectory of the bore path and may have special directional drilling systems on it to allow steering of the well to follow a particular trajectory. The drill string consists of a set of drill pipes, and accessories such as stabilizers, shock absorbers and downhole motors where it terminates with the drill bit. To achieve the necessary weight-on-bit, special thick-walled pipe (drill collars) provide the necessary mass near the bottom of the hole. Drill strings exceeding 10 km in length have been used to drill long-horizontal reach wells in the oil industry from land sites to reservoirs under the ocean, or to drill and develop many square kilometers of reservoir from one offshore platform.

In the oil industry, MWD (measurements while drilling) technology is used to determine the rock lithology and the borehole trajectory during the drilling process to guide the hole and change its trajectory. For the DBP repository, the guide hole drilling may be equipped with MWD, but given the diameter of the large boreholes, and given that the drilling follows the pre-drilled guide hole, there will not be a need for large-diameter borehole logging while drilling. Also, in air drilling or water hammer drilling, these systems cannot easily operate and are generally not available for large diameters.

During site investigation and development of a DBP repository, exceptional issues arising in the drilling of the pilot holes, the guide holes or the large diameter waste placement holes in terms of the nature of the drill string, including the bottom-hole assembly, are not expected. We note again that all of the necessary technologies currently exist in the mining drilling industry and the O&G industry, and that only minor operational changes will take place as the array of boreholes is developed. The use of well-seasoned technology is a safety asset and a means of reducing risk.

### 5.2.3 Drill Bits

Drill bits are the cutting tool used to gouge and/or break the rock located at the front of the drill borehole assembly allowing for the drill string to advance. There are different types of drilling bits used for various rock types (soft rock versus hard rock) and drilling systems (coring, conventional rotary drilling, hammer drilling). The major division of drilling bits for larger holes is rotary drilling bits versus hammers drilling bits. For small diameter core drilling, diamond drill bits and water circulation are standard.

Rotary drilling bits involve a rotating action of the drill bit either inline with the motion of the drill string (or downhole motor), or by rotating toothed cones pressed against the hole bottom. Fixed bits such as polycrystalline diamond (PCD) insert bits and diamond coring bits do not have rotating parts, but the bottom hole action of a rotating, "roller-cone" bit can be designed to accommodate lithologies from shale to dense sedimentary strata.

The most common roller drilling bit is the tricone design which utilizes three rotating conical heads. The tricone bit is divided into two major categories of bits: milled tooth and insets depending on the make up of the rotating heads' design, with toothed bits more common in softer rocks, and inserts more designed for harder rocks. The fixed cone bits are divided into several categories with the most prevalent bits being standards diamond drilling bits and polycrystalline diamond compact (PDCs). The PDC bit contains industrial diamond cutters that rotate on a single head instead of multiple moving parts. Rotary drilling bits are the most prevalent type of drilling bit with large diameter options commercially available. Figures 5-5, 5-6 & 5-7 shows examples of rotary drilling bits for hole enlargement and small and intermediate diameter percussion drilling bits.

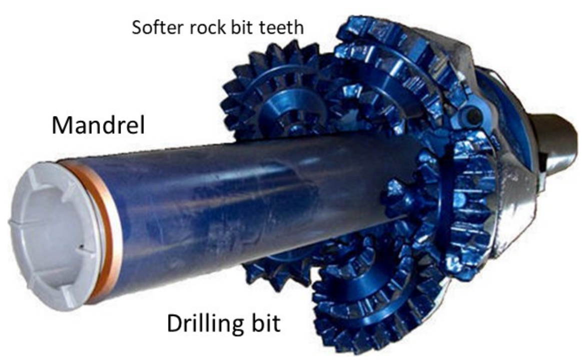


*Figure 5-5: Hole enlarging conventional rotary drilling bit, intermediate size, with toothed cones (Courtesy: Western Drilling)*

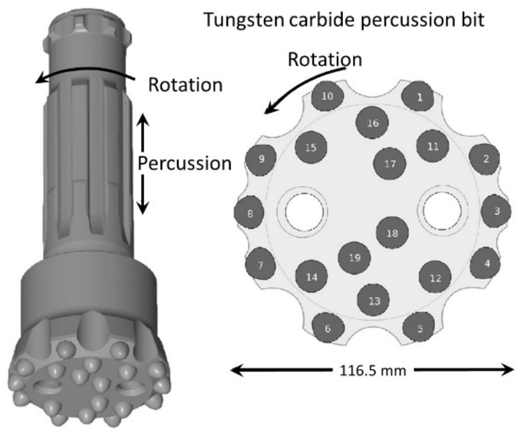


*Figure 5-6: Small-diameter tungsten carbide insert percussion drill bit – guide hole size*

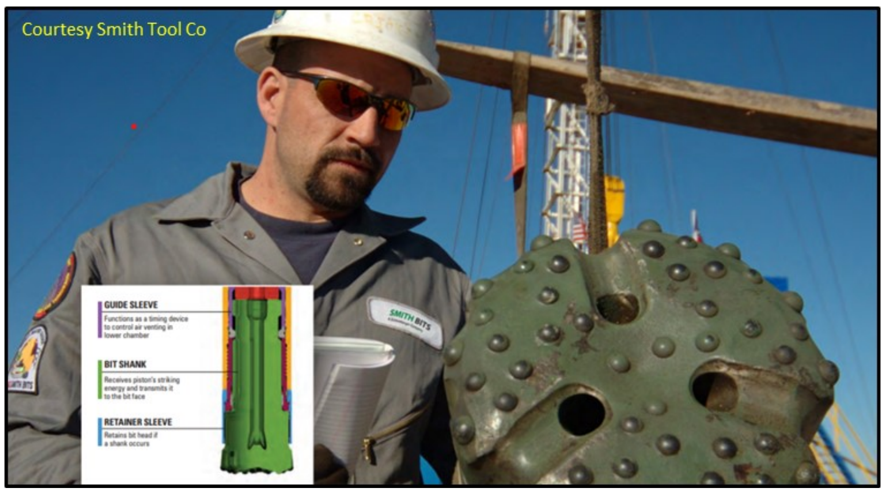


*Figure 5-7: Percussion drill bit with tungsten carbide buttons, intermediate size (Courtesy: Smith Tool)*

The mandrel hole-enlarging bit is for use with a guide hole. The example shown in Figure 5-5 has rotary cones for sedimentary rock, not hard rock. For the DBP system, the guide holes will be approximately 100-125 mm diameter, and the enlargement bit in the 600-800 mm range. Likely, percussion methods for enlargement to a 600-800 mm diameter will be used.

Figure 5-6 shows a 116 mm tungsten carbide insert drill bit designed for a small diameter percussion hammer with an external diameter of 100 mm, using conventional circulation methods. This is approximately the diameter of the guide holes for the repository development.

Figure 5-7 also shows a tungsten carbide insert drill bit for hammer drilling in hard rock and very dense sedimentary rock, approximately 400 mm in diameter, used in conventional circulating systems.

The other major group of drilling bits is hammer drill bits that are designed to resist both the torsional forces and the up-and-down percussive forces. Hammer drill bits utilize the pressure of the circulating fluid combined with the rotational energy of the drill string and transform it into percussive energy application while rotating. There are two types of hammer drills based on the fluid utilized in the system, pneumatic (air-powered) and hydraulic (water-powered or in some cases drilling-mud powered). Hammer drills are becoming more popular due to their higher penetration rates in strong, brittle rock, but at present are far less commonly used in the O&G drilling industry than rotary drilling bits. Furthermore, drilling of long and deviated boreholes, which is becoming more and more common in the O&G industry, is far more challenging for percussion methods than rotary down-hole mud pump drilling using PDC bits, which has evolved as the standard approach in the period since 2000.

Fewer companies manufacture large diameter hammer drills, compared to rotary bits, but projects that have the need for penetration are using deep hammer drilling more and more in high strength, brittle geological units. Companies manufacturing large diameter drilling hammers include: Center Rock[47], Wassara[48], Numa[49], and Drill King[50].

### 5.2.4 Drilling Mud

Designed drilling fluids, usually consisting of water or an oil-based liquid with various additives, are commonly referred to as “drilling muds” because the first drilling fluid formulations used in Texas were mixtures of natural clays and water, mixed by jetting in open unlined pits dug into clayey ground. Modern drilling muds are designed mixes of a number of components that serve many purposes in drilling O&G boreholes (see Chapter 1). These purposes include lubricating and cooling the drill string and drill bit, carrying cuttings from the bottom of the borehole to the surface, and stabilizing the borehole face to prevent excessive sloughing and borehole enlargement. The drilling mud “program” is an essential and vital part of planning a deep well in a sedimentary basin where geochemically sensitive rocks (shales, soluble beds…) will be encountered, as well as water, oil or gas under pressure, sometimes pressures so high that the density of the drilling fluid has to exceed 2.1 g/cc for control. Use of some chemicals and oil-based muds, disposal of cuttings, recycling or disposal of spent drilling fluids, and other activities associated with the drilling mud systems on O&G drilling rigs are heavily regulated in all jurisdictions. Most large drilling service providers have a range of services and products related to drilling mud. The largest and best-known companies are Schlumberger, Haliburton, and Baker Hughes, although locally there are many specialty companies with a great deal of experience.

We do not believe at this time that the DBP repository will require careful drilling mud choices and maintenance during drilling. The rocks at a qualified repository site will be very low-porosity rocks that are not chemically sensitive (e.g., no swelling shales or soluble strata), that are strong

[47] https://centerrock.com/

[48] https://www.wassara.com/en/

[49] https://www.numahammers.com/

[50] http://drillking.net/

enough so that borehole stability is not an issue, that contain no oil and gas nor artesian water pressures, and so on. It is almost certain that the large-diameter boreholes can be advanced with air or water as the drilling fluid. Exceptionally, we might envision the use of foam drilling if the boreholes are deeper than one km, and even the use of a simple water-bentonite slurry to provide better cuttings returns if the drilling choice is single-walled drill pipe with standard circulation.

### 5.2.5 Casing

Casing is usually a steel or aluminum tube that is rigidly coupled to the borehole wall with a cement that is pumped in to fill the annulus between the rock and the tubular casing. The casing's primary role is to provide support to the borehole wall after excavation, to serve as a barrier for drilling fluids to enter shallow formations, and to exclude in-situ fluids such as natural gas from affecting deeper drilling. On the +200 m deep surface casing of a repository borehole, it is possible to also install a blow-out preventer if abnormal pressures are expected.

Casings come in different dimensions, threads, and connection types. Casing strings in geothermal and O&G drilling have different purposes that change with the depth of the string: pressurized fluids exclusion, safety (BOPs), prevention of drilling fluid losses, rock stabilization, and production. The standard O&G well may have from two to five casings (see North Sea examples in Chapter 1) including a conductor pipe, surface casing, intermediate casing (one or two), special short casing strings hung from the intermediate casing, and a production zone casing with several perforated intervals. Casing of diameters ranging from 20 cm to over a meter in outer diameter are available "off-the-shelf".

Depending on the geology, in-situ pressures, geochemistry, and other governing factors, different dimensions and types of casing may be stipulated for different sections of the constructed borehole. It is assumed that the upper portion of the borehole is permanently cased to ensure the integrity of the near surface sediments (usually) and prevent contamination of the groundwater with the drilling fluid. Casing will likely be used at depth during construction to ensure the stability of the borehole in extremely deep scenarios. However, scenarios where the casing is removed prior to emplacement and/or closure are also possible, albeit unlikely in this project. If the casing is not removed, it will be required to be cemented and become a permanent fixture in the barrier system.

Steel is not geochemically stable over long periods. There is a remote chance that aggressive subsurface geochemical conditions can lead to the deterioration of the steel casing, leading to a situation where a pathway for radionuclides becomes more probable, although the decomposition products of steel (oxides, sulphides) are volumetrically greater than the metal, and this has a "self-sealing" potential. Because carbon-fibre reinforced epoxy resin casing will not degrade upon exposure to aggressive 'geochemicals', and is not to be exposed to ultra-violet light or other degrading agents, we suggest that the possibility of using large-diameter casing made from carbon-fibre reinforced epoxy resin with a suitable filler be seriously considered as an alternative to metal casing. Reinforced polymer oilwell casings have been available for several decades, and new developments continue (e.g., Hammami *et al*., 2012). Large diameter carbon-fibre/epoxy-with-filler casings are not an "off-the-shelf" item, but can be considered if it is deemed that the surface casing should stay in place and if a steel casing is deemed a radionuclide escape risk. Research shows that using a titanium dioxide filler powder in epoxy resins virtually eliminates issues of gamma radiation-induced depolymerisation (Craciun *et al*., 2011).

Another possible consideration for casing is to use a metal formulation such as Hasteloy™[51] that is exceptionally corrosion resistant.

*Figure 5-8: Carbon fibre or steel casing – which is better for long-term stability?*

### 5.2.6 Cement

We believe that the issue of cementing of boreholes in a deep large-diameter concept for canister placement should be examined carefully. We believe that this should be a research project that leads to the development of superior approaches to the sealing of the surface casing. For these depths, the strength of the final cured grout, whatever its composition, is essentially irrelevant; the viability of the grout lies in its ability to effect excellent rock-to-steel contact, sealing all possible pathways in the annulus (even to the point of entering the small joints in the rock mass), and retaining integrity indefinitely. Here are a number of points that must be considered.

- Conventional oil well cementing practice is inadequate for casing sealing and long-term barrier creation in a DBP repository configuration.

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[51] https://www.americanspecialmetals.com/HastelloyAlloys.html?gclid=Cj0KCQjwsuP5BRCoARIsAPtX_wGU7CyjhuAEIfEaK5WV0GKCqoZ1jbRc2Ws0zovBTk-o3kStwSbOoPgaAtkeEALw_wcB

  - Even with good practice, achieving a high-quality continuous seal is difficult.
  - Conventional oil well cementing uses water and cement powder, along with some performance enhancing additives, to generate a slurry with a density of about 2.15 g/cc. This cement slurry will experience some setting and post-set shrinkage.
  - Evaluating the quality of the cement-rock bond outside of a casing is challenging, as the acoustic techniques that are widely used are not unequivocally interpretable, and may give misleading information.
- Cement paste is geochemically unstable in the long term in many hydrogeological and geochemical conditions, although granites should provide a relatively benign geochemical environment.
- Grouts based on cement plus a filler are susceptible to a number of types of corrosion:
  - Carbonated (acidic) water – leading to "carbonation" alteration of the cementitious component
  - Sulphur (acidic) water – leading to weak sulphurous aqueous solutions that corrode steel and react with cementitious components
  - $H_2S$ long-term susceptibility

Thus, given even very low probabilities that groundwater chemistry might evolve or other conditions change over long time periods, we suggest the pursuit of a more secure approach to the grouting of casings, following these principles:

- If feasible, do not use geochemically unstable cementitious agents
  - Resins are available that can be pumped around a casing, specifically, low-viscosity epoxies that have a sufficient delay time for setting.
  - If a mineral cementitious agent is deemed necessary, develop a formulation with maximum geochemical resistance and use as little as possible, with the remainder of the slurry being composed of an inert granular filler.
  - If any compound (or mix formulation) exhibits shrinkage during set and cure, its behaviour must be re-examined and potentially modified.
- Use as much inert filling material as possible, yet retain the pumpability characteristics of low viscosity and reasonable wettability of the casing and rock surfaces
  - Silica, added in a range of grain sizes from 5 µm to 100 µm, is considered a good filler that is geochemically stable.
  - Carbon-fiber filler is considered geochemically stable.
- Avoid the use of additional chemicals (e.g., sulfonates for viscosity reduction) however,

- Examine the issue of rock and casing wettability, as a fluid phase that “spreads” on plastic and on the siliceous minerals in the rock mass is likely to achieve the best sealing bond.
- Certain additives that may lead to a minute amount of expansion upon set and cure (a fraction of a percent) may be considered if they do not lead to geochemical instability.

- Exercise the best possible practices during cement placement.
  - Aggressive casing reciprocation and rotation during placement using the top-drive systems currently available mean better flow around the casing.
  - Equip the casing string with strong plastic centralizers and scratchers to help establish a centralized casing and good contact with a borehole wall.
  - Consider other methods that might give better results, such as increasing the density of the cement or plastic grout with an inert mineral filler.

### 5.2.7 Deviated Drilling

Deviated drilling is a “steerable” form of borehole drilling where a bore is drilled along a pre-determined trajectory to a subsurface target. At a predetermined depth, the borehole path is deliberately deviated, often from an initially vertical orientation; this is known as the kickoff point. Multiple drilling trajectory profiles are possible, ranging from a fully horizontal borehole trajectory to a slight deviation, such as the 10° outward deviation suggested for this project. Some well-used examples in the O&G drilling industry include an initially vertical bore deviated to horizontal; a vertical bore deviated diagonally to follow a straight but inclined course (with dip angles as small as 10° in long-reach wells); profiles involving multiple bends and directional changes to avoid known faults; and, multiple bends to follow a single stratum that has considerable structural variation. The depth and overall borehole path are usually a function of the starting position, the overburden, and the relative location of the target formation. It is unknown at this phase if any directional drilling is required other than maintaining the outward inclination angle of the guide holes at 10°. Also, in the case of the diamond-drilled core holes used for the pilot holes, it may be desirable to have inclined boreholes to intersect more of the natural vertical fractures that may exist at the site.

The bottom-hole assembly for directional drilling is similar to the equipment used in traditional vertical rotary drill rigs. Additional stabilizers, motors, and measurement while drilling (MWD) equipment are employed to control inclination and deviation angle to steer the bore. Conventional directional drilling has the downhole motors attached at the end of the string to apply the rotation necessary to the drill bit. The steerable driving system provides real time data to the operator allowing for some corrections and the collection of geological data.

Rotary Steerable System (RSS) is a deviated drilling technology which allows for full three-dimensional directional control while drilling with the drill string rotation. An additional component is required to be included in the drill string to direct the well path called the rotary steering device. Depending on the system employed, the internal mechanics and processes behind how the system steers the well head differ. The RSS also communicates information to the surface in a manner different than conventional directional drilling system employing a much more integrated system and denser packed position of MWD and logging while drilling systems.

Deviated drilling technology is prevalent in the O&G industry with many companies providing deviated drilling services and equipment. However, larger diameter deviated drilling in mining is relatively uncommon compared to deviation of smaller diameter holes typically used for extraction of oil and gas. Commercial tooling is available to be incorporated if a deviated solution is designed for the pilot holes, guide holes or final large-diameter boreholes.

At present, other than constant dip angle diamond drilling or small-diameter guide-hole drilling, challenging deviation control is not considered an issue for the DBP repository: we recommend straight but gently inclined large-diameter boreholes.

## 5.3 Commercial Drilling Companies

It is uncommon for an organization that is commissioning a well or borehole to own the drilling equipment and have as direct employees the personnel that actively construct the borehole. Drilling equipment with a crew is typically rented from a drilling contractor to complete the required construction, and the full drilling service provider owns a fleet of equipment that can meet the needs of the client. Because of the uniqueness of a deep borehole concept implementation for the placement and isolation of nuclear waste, it is possible that a drilling contractor may not possess the required tooling or rigs to construct the project. The work of other drilling service providers may be required to meet particular challenges (e.g., if large-hole packer grouting is deemed necessary). This could include contracting a drill rig and tooling manufacturer to modify or build equipment for special purposes in such a way that the drill rig can use them without rig modifications. We believe it is unlikely that a purpose-built drilling rig is required to meet all the technical and safety criteria to construct the deep borehole. That said, purpose-built wireline systems for canister placement and coiled-tubing workover equipment for barrier placement may be needed.

The following section provides an overview of different types of commercial drilling companies. The services range from supplying drill tooling to construction of speciality rigs to consultation and operation of drilling operations. Selected companies are highlighted and used as representative organizations that are well known in the field. This section makes no attempt to develop an exhaustive list of all service providers or provide an endorsement for any named company. The DBP repository technical committee will make the decisions relevant to designing a responsibility and safety framework that is flexible and meets the needs of the project.

### 5.3.1 Project Operators (Primary Client)

The project operator is the organization that is charged with the design, implementation, operation, and closure of the borehole repository; this would be role of Norwegian Nuclear Decommissioning (NND) in Norway.

In the case of the deep borehole waste placement concept, this means that the project operator is also the direct representative of the owner of the waste and may be considered to be the “waste management and isolation organization” for the life of the project and beyond. In Norway, NND will be both waste owner and project operator. The operator’s roles include design of the facility based on the lifecycle analysis of the borehole and specification of the design and materials/labour required. Once a plan has been developed, it is the operator’s role to retain qualified contractors and service providers to action the borehole construction. The drilling operator will likely work in conjunction with consulting engineering firms due to the technical complexity of the project. The relationship and roles of the drilling operator and retained consultants can vary and will have to be scoped in any service agreement developed.

### 5.3.2 Drilling Engineers and Technical Experts

The drilling engineer acts as the agent of the project operator (the client). Drilling engineers provide specialized engineering services as a company or in some cases as sole practitioners, and they are hired by the project operator because of a high level of knowledge of the details of drilling, in-the-field experience, and a deep understanding of the reasons for the repository design. In general, the drilling engineer is involved after the site qualification is complete and participates in the FEED (Front-End Engineering and Design) phase of the project (see Section 7.3), carrying on as the design is executed. The drilling engineer’s role can vary significantly depending on the service agreement with the project operator, but it is common practice in conventional drilling activity to give the drilling engineer full authority during drilling operations, reporting to the project operator on a daily basis through a formal reporting procedure. If drilling is carried out 24 hours a day, the drilling engineer may have one or more subordinates acting on their behalf, or the drilling engineer may stay on site to make necessary decisions as they arise.

Retaining a drilling engineering consultant is not necessarily a requirement if the technical and managerial expertise already exists “in-house” with the project operator; however, due to the complex nature of the project, it is unlikely that a solely “in-house” solution exists. It is far more likely that a team of experts in several specialized domains provide advisory services for the drilling project on an as-needed basis. For example, a rock mechanics expert may be required during the qualification process to classify rock, and this person may be available during the large-diameter drilling program. The need for expertise will particularly be the case with in-situ hydraulic testing because there are very few consulting firms with expertise at testing and test analysis for the extremely low hydraulic conductivities required, i.e., $\leq 10^{-13}$m/s. Casing and cementing advice may be provided by a domain expert, and so on. The widespread use of domain experts is standard practice in the O&G industry and the mining industry: whenever a specialized service is required, a domain expert, perhaps employed by the service provider, guides the provision of the service.

### 5.3.3 Drilling Contractors

Drilling contractors are companies that own and operate the drilling rigs and employ the crew used to operate it. A drilling contractor may be a large integrated corporation, or a smaller corporation that has particular experience in the type of drilling to be carried out. The role of the drilling contractor is to drill the borehole with the supplied rig and crew, following the drilling program developed by the project operator and the consulting drilling engineer. For most standard drilling operations, the drilling contractor will have the required tooling and equipment to complete the drilling project. However, due to the complexity of drilling an array of slightly inclined, deep large-diameter boreholes at a single site, some commercially available niche equipment may have to be procured for the drilling contractor to complete the work. The drilling contractor is directly responsible for the safety and welfare of all personnel on site who are employed directly, and the drilling contractor has the right to invoke all of their own corporate safety rules, in addition to the safety procedures agreed to by the project operator and drilling engineer.

In many cases drilling contracts are written on a per-metre basis, providing an incentive for the drilling contractor to be efficient and conscious of time. In the case of a DBP repository, such a contract is improbable, and day-rate rental will be the financial basis of the agreement.

### 5.3.4 Drilling Service Providers

Drilling service companies provide speciality services not provided by the drilling contractor. These service providers are either retained by the drilling contractor or by the drilling engineering consultant, depending on the service agreements. Some examples of drilling services include cementing, fluid management, downhole testing programs, and geological logging. Some examples of specialty service providers in the O&G industry include Schlumberger, Baker Hughes, and Haliburton. Given the specialized nature of the project, many of these services might involve more direct cooperation with the project operator employees. An example might be the need to conduct specialized testing downhole, interrupting the active drilling, bringing in a specialized service provider on a short-term basis. Drilling service providers do not usually operate on a stand-by basis, but given the number of holes chosen and the data collection program, certain services such as geophysical borehole logging may require stand-by equipment and personnel rental.

### 5.3.5 Drilling Rig and Tooling Manufactures

Drill manufactures design and manufacture drill rigs, machinery, tooling, and other drilling accessories. In standard mining or O&G projects, it is unlikely that the drilling operator will have to engage with the manufacture of the drilling equipment, which is owned by the contractor, not the manufacturer. Due to the complexity of deep borehole drilling in strong, stiff rocks (higher depths and larger diameter at depth) it may be required that the drilling operator, in consultation with the project contractor and the drilling engineer, acquire commercially available drilling equipment that is not in the drilling contractor's inventory. This can be done by liaising with the drilling equipment manufacturers. The design of a purpose-built rig, manufactured with commercially available equipment, is a potential requirement for this project, although we favour using standard equipment and procedures as much as possible to minimize unforeseen equipment issues.

An example of a speciality tool is if the design project leads to the choice of water hammer drilling. Water hammers are a commercially available tool, but it is possible that local drilling contractors do not possess one of the right diameter, along with the pump capacity to actuate it. In such cases, procurement or rental agreements are made so that the project can achieve the design parameters with the drilling contractor's equipment.

## 5.4 Small Diameter Drill Holes: Pilot and Guide Holes

At this time, we recommend that pilot holes for site qualification be small diameter core holes advanced by conventional continuous coring diamond drilling systems.

Figure 5-9 shows a diamond coring exploration drilling rig that is commonly used in the mining industry. The term "diamond" drilling does not preclude the use of other types of bits as appropriate. The design team for the project will have to choose the core and the bit diameter to achieve the technical and scientific goals, keeping in mind that some geophysical tools may need certain minimum diameter holes. We also recommend that pilot holes be kept to smaller diameters as much as possible, so that sealing is more straightforward. We have suggested NX coring as sufficient for standard characterization purposes, but this means that if a standard NX core bit is used, the standard outer diameter is about 74 mm. If this size is too restrictive for logging and testing, HQ (96 mm OD) or PQ (122.6 mm OD) may be chosen. As before, we recommend standard sizes for the drilling equipment.

*Figure 5-9: Diamond coring exploration rig, deviated hole (Courtesy: Layne Christensen Drilling Co.)*

The borehole diameter recommended for the guide holes are in the range 75-125 mm, and this size range is lower than the typical size range for an oilfield drilling system. For the guide holes, given that the site has already been qualified, it is not necessary for full-hole coring, although coring may take place along desired sections such as the 100 m above the canister section. We recommend that the guide holes be advanced with air or water hammer drilling, and that the guide hole be compatible in diameter with any diamond core barrels that may be used during guide hole drilling.

## 5.5 Summary and Recommendations

We recommend that the development of the DBP repository employ the use of standard mining industry drilling equipment in standard sizes as much as possible. The main reason for mining equipment and mining expertise is that the drilling activities will traverse crystalline or indurated sedimentary rocks at a repository site, and the mining industry has a long history of drilling in granites, strong and stiff sediments, greenstone intervals, and other extremely low porosity rocks. For example, in the gold fields of South Africa, the gold seams at depth are found in ancient sediments – quartzites and greenstones – and with igneous rocks such as diorite dikes and sills. The quartzites and greenstones have experienced low-grade metamorphism, and the porosity is essentially zero. Exploratory diamond drilling with coring has exceeded depths of 4 km in this area.

The main reason we recommend standard equipment is that the proposed activities are all standard, suitable equipment is available, and highly experienced companies exist in Scandinavia and the rest of Europe. Final borehole, pilot hole and guide hole diameters and casings should be selected from standard available sizes to accommodated standard downhole tool sizes. Note that drilling activity precedes canister emplacement and can progress rapidly in a conventional mode.

More specifically, for the three phases of drilling, we recommend the following deployments:

- For pilot hole drilling, we recommend a standard NX (54 mm core, 75.5 mm OD) size diamond core drilling, wireline retrievable core barrel, for the entire depth, generally with full core collection.
    - There may be exceptions to this recommendation if certain needs are stipulated during the site qualification process relating to:
        - Potential need for larger-diameter rock cores for larger-scale rock testing;
        - Potential need for larger-diameter boreholes for obtaining geophysical log properties, or where there is a minimum diameter for logging tools available; or,
        - Potential need for a larger diameter to carry out double packer tests, for installation of special monitoring devices, for overcoring stress measurements, and so on.
- For guide hole drilling, we recommend inclined drilling using appropriate directional control technology and mining industry exploration capabilities. The holes may be advanced with several different approaches, depending on the outcomes of the exploration phase and the decisions of the repository technical committee:
    - Diamond drilling with full coring if the technical committee decides this is necessary for QC/QA on the entire set of DBP repository holes;
    - Diamond rotary drilling with coring of pre-identified specific zones of interest, and diamond drilling with no coring for all other intervals;
    - Small diameter percussion drilling with air hammer or water hammer technology, with collection of drill cuttings for examination, but no coring; and,
    - As above, there may be exceptions, and larger diameter guide holes stipulated for reasons similar to those mentioned above.
- For large-diameter deep waste placement boreholes, we recommend air hammer and water hammer percussion drilling with reverse circulation, using large diameter percussion hammers with a mandrel guide that fits into the pre-drilled guide hole. This drilling rig must also have the capability of setting casing during the drilling program.

- The hole for the short conductor pipe to protect the near-surface open fractures in the rock mass is drilled and the conductor pipe (casing) centralized and cemented with a high quality, geochemically suitable grout. (Alternatively, the conductor pipe hole may be pre-drilled with a smaller percussion drilling rig before the large, deep-hole rig is used.)
- The surface casing, to 200 m minimum, depending on site qualification results, is drilled to a diameter sufficient to place casing and cement (or otherwise seal) the centralized casing into place. This casing, at this time, is assumed to be a minimum of 660 mm internal diameter to allow drilling the 600 mm diameter final placement hole in this scenario. Standard sizes should be used.
- The DBP repository technical committee, depending on the site qualification studies and the final choice of canister diameter and barriers, may alter some of these suggested dimensions.

The required drilling equipment to execute these tasks is largely commercially available, and there exist many drilling service providers because of the extent of the mining industry capability to drill large diameter holes. Once final decisions are made on the diameters and the isolation practices for the waste canisters, standard diameter sizes should be used for the surface casing and the boreholes to avoid “special build” systems.

There should be no significant safety or social issues in retaining the required drilling equipment and personnel to construct a deep borehole array for the placement and isolation of nuclear waste. All exploration and development drilling on site should be completed before any actions related to waste emplacement begin.

We believe that, for the most part, “off the shelf” solutions for the drilling activity exist. By liaising with companies in the mining drilling industry at the late stage of site qualification, before the final FEED activity (Section 7.3), the appropriate solutions using commercially available equipment and standard sizes should be accessible to construct this project with excellent efficiency and full QA/QC of the outcomes.

# Chapter 6: First-order risk assessment

## 6.1 Overview of first-order risk assessment

The indefinite term storage of nuclear waste is appropriately viewed by society at large as a "high risk" undertaking because of the potential severe consequences associated with exposure of humans and the environment to significant concentrations of radioactive material. Although severe consequence events can be hypothesized during a scenario-modeling activity, and they should be hypothesized, analyzed and evaluated, the remit of this review is limited to the risks related to the handling, placement, isolation and long-term residence of the radioactive waste once it arrives on a qualified site.

Risk associated with processes such as vitrification, encapsulation, and transportation of high-level wastes to the DBP repository site are beyond the remit of this discussion. Compaction, packaging and shipping of any low- and intermediate-level waste to the DBP repository site are also beyond the remit of this report. The overall risk in these pre-site activities appears to be manageable with appropriate precautions taken, the development of detailed operational plans, and the use of high-quality engineering and transportation practices. These steps reduce the probability of severe consequence events occurring, and consequentially the risk. Furthermore, the potentially severe consequences of an event involving radioactive waste are dominantly associated with the high-level waste canister contents; hence, we will not broach the subject of risks related to the activities surrounding low- and intermediate-level wastes. Not being formal risk analysis experts, toxicologists, nor accident analysts, we cannot comment on the procedures involved.

However, given our experience in the O&G industry and subsurface geomechanics issues, engineering geology, drilling engineering, thermohydromechanical modeling, mining and other areas, there are many risk issues that we can comment on, if only in a qualitative or semi-quantitative manner.

It is our opinion that high-level radioactive wastes, appropriately encapsulated in multi-barrier canisters in a chemical condition of low solubility, can be securely isolated indefinitely in large-diameter boreholes drilled deep into a competent and tectonically inactive rock mass in Norway. This is a technical assessment, largely devoid of social issues.

*Technical Risk and Social Perception*: There are many published treatments of radioactive waste issues that deal with social issues in the context of technical factors. Extensive literature is available throughout Europe's nuclear nations related to social issues and wastes. We suggest that the NWMO – Nuclear Waste Management Organization of Canada – is a valuable source of public information related to various dimensions of radioactive waste management, ranging from social perceptions, indigenous issues, transportation, and so on. All technical and sociological reports, minutes of meetings of various committees, site assessments and communications can be found online.[52] For example, an important document highly relevant to this report is NWMO (2017) TR-2017-02, treating technical issues associated with a high level spent fuel repository in crystalline rock. Because there is a high probability that the final repository site chosen in Norway will be in crystalline rock, the observations of that report (among many others available at the same site) are relevant to the Norwegian waste management program.

Other reports (e.g., Dusseault *et al.*, 2014) done through the NWMO for Ontario Power Generation Inc., the major state-owned power generation company in Ontario, Canada address the social perception of risk as well as interactions with Indigenous communities that could be affected by radioactive waste placement activities. These reports contain valuable insights for many aspects of radioactive waste management that the Norwegian government agencies will encounter on the pathway to develop a deep borehole placement repository in strong stiff rock.

A major source of technical and scientific information related to waste placement in crystalline rock masses is the SKB site, the Swedish Nuclear Fuel and Waste Management Company portal.[53]

The Finnish government nuclear waste management program has qualified a site in crystalline rocks, and much information is available.[54]

The objective of this chapter is to review first-order risk assessment issues for construction, operations, and post-closure scenarios, events, and processes that could affect the DBP program. With appropriate first-order risk factors identified, future engineering design work can be planned for detailed analysis to ensure that an acceptable level of risk is maintained for these and other identified factors. Discussion will be provided throughout as to how to potentially mitigate the consequence of events or lower the probability of their occurrence. Additionally, typically referenced issues in the nuclear waste management literature will be brought up to discuss the validity of the risk concept in the context of a DBP repository program.

The first-order risk assessment provided in this report does not present estimates of the probability and consequences of different events. Once a firmer understanding of the design and development process exists, a more quantified analysis starting with the study of NWMO documents and the Swedish-led waste placement studies should be undertaken. These two information sources are perhaps the most comprehensive means of accessing data on crystalline rock repository studies, although the NWMO also has a great deal of relevant information on a

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[52] https://www.nwmo.ca/en/Reports

[53] https://www.skb.com/publications/

[54] A good summary of the Finnish program for radioactive waste management may be found at https://vnk.fi/documents/1410877/3437254/Finnish+Research+Programme+on+Nuclear+Waste+Management+KYT2018+12112014.pdf

sedimentary rock mine repository plan in low-porosity, low permeability Paleozoic strata in southern Ontario at the Bruce Nuclear site.

The SKB, Finnish and NWMO websites list and provide access to many valuable studies for crystalline rock and although they focus on an "underground mine" concept, the issues are relevant and similar. We point out that the multiple barrier concepts, canister design, barrier stability, and many other factors are similar, but the concept of deep boreholes in crystalline rock is not explicitly addressed. We believe that the technical issues related to risk in a DBP repository are simpler and more manageable than for a complex underground mine because of surface operations and modularity.

This first order assessment will try to provide quantitative values where possible to supplement the qualitative assessment.

### 6.1.1 Public Views of Risk

Risk is widely discussed and studied; yet, risk remains significantly misunderstood by the general public and even by experts. No human activity is without risk. All industrial developments carry an array of risks and benefits, as does the study of nuclear processes in research reactors. It is the responsibility of the engineers and scientists involved in these activities to identify the risks, to delineate the probabilities and the consequences, and to seek to mitigate the consequences and reduce the probabilities, as much as is reasonably achievable.

Experts differentiate clearly between personal risk and general risk (Sjöberg, 2003). A personal decision involving risk is choosing to drive a vehicle on a public road. Everyone is aware of the risks, as fatalities and accidents in Norway are widely published, and safe driving programs are promoted on various media outlets. Individuals believe that they are personally capable of controlling the level of risk through personal behavior (respecting all the rules) and personal capabilities ("good reaction times" or a high level of experience). Individuals therefore rarely evaluate the risk involved in a personal car trip, except perhaps in extreme weather conditions when repeatedly warned by the media, friends, or observed events.

General risk is, for example, the risk of radioactive waste pollution of a watercourse from an accident involving a canister during transport. The individual has no control over the risk involved, no intuitive or experience-based appreciation of the consequences, and as a result has a completely different perception of the risk levels. This is one of the reasons that all responsible agencies recommend that a radioactive waste repository selection process and all of the deliberations and studies that go along with it must be public, transparent, and without manipulation or coercion. Because general risk always has an extremely low level of tolerance to all individuals, only a very low perceived risk level can be tolerated. This creates a challenge to the technical managers of a radioactive risk repository because of the need to understand and explain to the public the meaning of extremely small risks, either small probabilities, trivial consequences, or both. North American experience indicates that the public substantially overestimates its risk from nuclear-waste disposal compared with engineering risk assessments and will seek to divert any DBP far away from their respective communities.

This section addresses the meaning of the term “risk” in an engineering or industrial context, but even in technical areas, many definitions exist that are slightly different.

A download from this listed site[55] in 2014 found a definition of “risk”:

“A probability or threat of damage, injury, liability, loss, or any other negative occurrence that is caused by external or internal vulnerabilities, and that may be avoided through preemptive action.”

The elements of the definition are underlined above, and stated here:

- a potential for a negative outcome
- being related to vulnerabilities that can be identified
- capable of being avoided (or mitigated)

This definition associates risk with probabilities, consequences, and an ability to be mitigated; it is suitable for use in the Norwegian repository context.

Even in the scientific and technical literature that has been independently vetted there are differences in interpretation and impact assessment estimates, especially in the area of environmental and public health risks associated with radionuclides and potential escape into the biosphere. Part of the challenge in arriving at a scientific consensus on issues such as risk presented by a radionuclide repository to long-term public health and the attendant environment impacts may lie in a lack of detailed studies over a sufficient time frame to allow reasonable assessments to be made. This is the case for a nuclear waste repository, and always will be: using a generation or two of scientific and technical assessments to design a repository for a thousand generations will always encounter this challenge. Hence, very low levels of risk must be sought through making the probabilities of escape extremely small (e.g., multiple barriers), or reducing the consequences (e.g., massive dilution if escape should happen).

Difficulties in making rational and carefully weighed assessments of risk arise within groups of highly skilled scientists and engineers, who each retain individual perceptions of consequences that can differ widely. Alone, simple cost-benefit analysis is not viable in the case of radioactive waste isolation engineering.

[55] BusinessDictionary.com. Retrieved August 30, 2020, from BusinessDictionary.com website: http://www.businessdictionary.com/definition/.html

### 6.1.2 The Engineering Definition of Risk

All quantitative or semi-quantitative risk assessment entails the concepts of the **probability of an event and consequences of an event**. Risk cannot be said to be zero in the case of a human construction endeavor, such as a DBP repository, even if the risk is remarkably small. The concept of the probability of an event, or of the consequences of an event should it occur, should be devoid of misleading or erroneous perception.

The engineering concept of risk is often presented as a simple non-quantitative equation:

**R = P×C** - **R**isk equals **P**robability times (negative) **C**onsequences

In many cases, risk must be expressed semi-quantitatively (statistical probability of a storm of a certain intensity…), or in a relative manner (more than…, much less than…). For example, "The probability of significant radionuclide escape from a DBP repository is much lower than for a surface repository" is a relative statement; quantifying the different probabilities is a challenge.

Engineering risk analysis not only deals with the event probability in time and in space, but also the probability of various consequences (e.g., the number of human doses of various levels from possible exposure after an event). Earthquake engineering provides an example. The **probability** of an earthquake of a particular magnitude over a period of time (say 30 years) can be expressed as a fractional number or percentage: "There is a 30% probability (P = 0.30) of an earthquake of Richter magnitude 5.0 or larger in a specified region over the next 10 years." Or, for a rainfall event: "There is a 5% probability in any single year of a 24-hour rain event exceeding 25 cm of rainfall in Bergen (or other region)." These probability statements are not complete risk statements: they say nothing of the consequences. A magnitude 5.0 earthquake in Oslo would have far greater consequences than if it had occurred in Røros, a remote and lightly populated region. So, the risks associated with a 5.0 magnitude earthquake in Oslo are clearly far greater than the risks associated with a 5.0 earthquake in the Norwegian hinterland.

The **consequences** of such an event are more difficult to specify, but statements such as the following can be made if reasonable data are available: "It is estimated that there is a 50% probability of flood damage of NOK15 million if 25 cm of rain falls in a 24 hour period in Bergen; however, the risk to life is estimated to be small, with less than a 10% probability of the loss of a single life as a direct consequence of flooding." This type of quantitative risk analysis can be used by communities and governments to make decisions about infrastructure investments, and in the case of potential industrial developments, assessments of the impacts that might ensue. Public health risk assessment is an important task; an evaluation of the public health risks related to the DBP repository project is needed to lead to clarity; this will be based on the probability of various events that could lead to the escape of radionuclides into the biosphere over long periods of time.

The issue of radioactive material impacts on humans is related to the dose of radiation received over what time frame. This is a widely studied area in radioactive waste management and we do not have comments on this subject, given that the remit of this report is to assess geo-risks, and more specifically, geomechanics risks associated with the concept of deep borehole placement of wastes.

It is possible to rank risks semi-quantitatively and comparatively on the two axes of **probability** and **consequences**. Figure 6-1 shows how this is done.

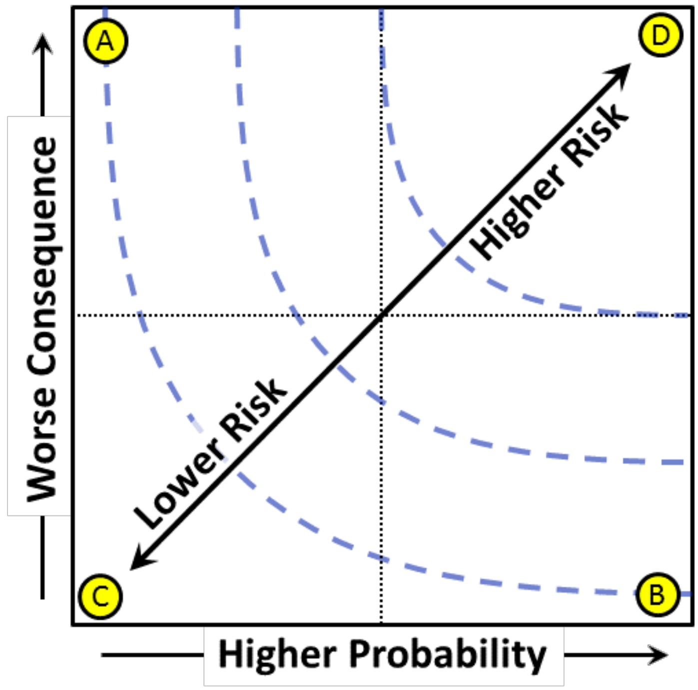


*Figure 6-1: A plot of Probability vs. Consequences helps quantify relative risk*

On the left-hand side, the probability of an event occurring (e.g. in a given 10 year period) is not zero, but it is exceedingly small. In contrast, on the right-hand side, the probability is so large as to be almost certain over a period of time, depending on what type of events are being discussed. The blue dotted lines may be considered to be contours of “equal risk”, such that an extremely improbable event carrying severe consequences (“A” on the plot) carries an overall “risk level” similar to a low-consequence event that has a high probability of occurrence and recurrence (“B” on the plot).

In geology, it has been said: “Improbable events, given geologic time, become virtual certainties.” In the radionuclide waste time frame, because the radioactive species have different energy emission levels and different half-lives, the consequences of an escape inexorably decrease with time, although the probability of an event inexorably increases with time. This gives an important insight into risk mitigation actions:

- They should expand the time frame for the probability of an event occurring as much as is reasonably possible; and,

- They should reduce the impact of such an event (for example, by reducing the emitted dosage through radioactive decay).

The level of radioactivity in waste becomes less and less over time, depending on radionuclide species and concentrations. Quantifying risks remains a challenge for the repository project technical committee and its experts in the context of radioactive specie behavior and canister design (how much waste per canister and what is the nature of that waste over what time period?).

## 6.2 First order design and construction risk

Although the principles of Adaptive Management (Linkov *et al.*, 2006) will be used to mitigate risk, decisions made prior to and during the construction of a DBP facility will impact the project's overall risk. This section is an acknowledgement that construction and design issues will be made under conditions of uncertainty. Future analyses should make sure to carefully consider their implications on the overall safety during the operations and post-closure stages of the project: uncertainty reduction is important.

Compared to the other two stages of the project (operations, and post-closure), the construction phase does not entail risk associated with the exposure of humans and the environment to radionuclides. We assume that during site qualification and borehole development, no nuclear waste will be on-site. Any materials that are stockpiled for future placement (e.g., low-level waste capsules) will be stored in a secure facility away from active construction operations. Nonetheless, construction and design decisions will impact barrier implementation and therefore affect the future conditions of the natural and engineered barrier systems' ability to inhibit the escape of radionuclides. For this reason, the following section is divided into two separate sections: construction events with significant short-term risk, and design and construction activities and decisions that will influence the post-closure risk.

### 6.2.1 Construction risk events

Construction risk events are potential scenarios that could occur resulting in the immediate halt of construction. The risk inherent with these events is tied to economic losses associated with damage to infrastructure, machinery, or loss of man-hours due to shut down. Leaving aside issues related to equipment breakdown, potential construction risks include but are not limited to these "geomechanical" subsurface events:

- Borehole collapse (or severe loss of functionality)
- Borehole misalignment
- Casing failure (failure of the seal in particular)

*Borehole Collapse*: Borehole collapse is the structural failure of the borehole resulting in the borehole walls raveling or caving into a portion of the borehole. This can occur during active construction (while drilling machinery is downhole) or after completion of the borehole. Factors affecting the potential for borehole collapse include: in-situ stresses, pore pressures, drilling fluid, and rock strength and mechanical properties. Depending on the severity of the collapse potential, consequences range from temporary shutdown of construction operations to allow for repairs to abandonment of the borehole. All consequences will result in economic losses as equipment is placed on standby while a solution is developed.

We perceive that the following rock mechanics issues govern the probability of borehole collapse or loss of function:

- The in-situ horizontal stresses, both in absolute and relative values;
- The strength and nature of the rock mass matrix;
- The intensity and geometry of the natural fractures in the rock mass (frequency, spacing, orientation with respect to the borehole); and,
- The presence of features such as pre-existing faults or intensely fractured zones that intersect the borehole trajectory and could be remobilized during drilling or contribute unconsolidated material to the borehole in an unexpected manner.

Risks can be mitigated during early site selection and site qualification through the following activities:

- Continuous assessment of the magnitude of the horizontal stresses through a set of qualitative and quantitative estimates of the stress levels through tectonic history, seismic history, and direct measurements using overcoring methods, pilot hole ellipticity methods, seismic anisotropy, and so on. Excessively large differential stresses may disqualify a site, or may lead to decisions such as recommending a deeper borehole for waste placement.
- Continuous assessment of the nature of the macroscopic discontinuities in the rock mass (joints, bedding planes, sheared surfaces, fault zones, intensely factured zones, significant lithological differences, large differences in mechanical properties…). This is achieved through continuous structural geology assessment though seismic analysis (VSP, cross-hole…), borehole televiewer analysis, core examination, and related activities. Identification of excessive fracture frequency and poor condition of macroscopic discontinuities during site qualification and drilling could disqualify a site, or disqualify individual boreholes for acceptance of high-level waste canisters.
- Assessment and qualification of the rock matrix strength through index tests, geophysical logs, and other means during site qualification and guide hole drilling for each borehole to estimate the probability of borehole spalling that could impair activities.
- "Criticality evaluation" of linear features to assess how far they are from a condition of shear slip and what are the probabilities of causing such slip by drilling activity or later repository thermal effects.

Note that the value of the vertical stress is not considered a risk because the degree of uncertainty associated with it is very small, in comparison to other stress values. This is likely to be the case in Norway where glaciation has removed significant overlying rock.

*Borehole Misalignment*: Repository boreholes will be drilled along a predefined alignment terminating at a specified design depth: the base case scenario suggests a 10° inclination from vertical, and a depth of 1 km. The specific depths chosen may vary from these recommendations but we consider it important that the boreholes are properly aligned, and relatively straight, so that no impediments to canister and sealant material placement exist. It is possible that a DBP repository is designed with two sets of boreholes: deep boreholes (e.g., 2 km) for high-level waste canister placement, and shallower boreholes (e.g. 800 m) for the placement of intermediate- and low-level waste capsules. Part of the design will be to reduce the thermal impact of the radioactive waste emissions on the rock mass to a level low enough that there is minimal risk of thermoelastic stresses developing that could allow unwanted slip along favorably inclined discontinuities. This means that the high-level waste canisters will be placed some distance apart, both vertically and laterally, such as to allow the early time thermal response (first hundred years) to be inconsequential.

Also, it is widely accepted that the longer the potential flow pathway of released radionuclides in the groundwater flow system that hosts the site, the lower the risk, all things considered. There is a risk that misalignment leads to development of potentially shorter pathways but this is unlikely given the great depths of emplacement anticipated. In the situation of limited deviation (less than 10° or shallower depth), the closer spacing of the boreholes could result in regions of higher temperature contrasts with surrounding regions, leading to localized stress concentrations resulting in slip of favorably oriented discontinuities, creating preferred pathways. For a severe misalignment case, a borehole intersecting an existing borehole or pilot hole would likely result in abandonment of both holes.

We perceive that the following issues present a risk that the final borehole alignments are not satisfactory:

- Inappropriate decisions as to the number of boreholes such that the canisters may be too closely spaced for acceptable heat dissipation, given the uncertainties in long-term behavior of the rock mass response.
- Inappropriate geometry of the borehole array that gives a greater probability of shorter pathway potential development.
- Poor quality guide hole placement.
- Failure to precisely verify the three-dimensional trajectory of all pilot holes and guide holes.

These misalignment risks can be mitigated by a conservative yet appropriate approach to the design of the DBP repository.

- The decisions as to the numbers, depths and geometrical disposition of the placement boreholes must be made with high-quality structural geology and engineering geology information that is acquired and extended throughout the process and stored in the GEM. If there are consistently oriented sets of discontinuities, placement borehole locations may be altered to reduce shorter pathway development probability.
- Based upon careful simulation backed by direct full-scale heating experiments and knowledge of the constitution (thermal output) of a canister, alignment risk mitigation will involve uncertainty analyses (e.g., Monte Carlo simulations, Markovian walk simulations, Bayesian analysis for impacts…), and design decisions made at levels of 95% certainty of outcomes. These models can be applied broadly, and for each individual borehole, once data are available.
- The use of guide holes for the large-diameter borehole drilling will eliminate the risk of borehole misalignment, providing that the guide hole drilling method is appropriate, directionally controlled, and verified by a detailed guide hole survey and structural geology assessment for the borehole.
- An acceptable criterion must be established for the offset distance between pilot holes and the final large-diameter placement boreholes to reduce the probability of a shorter pathway development.

The decisions for optimum borehole placement are updated continuously as more information is available to populate the GEM. Once the structural geological condition of the subsurface becomes better understood, the geometrical disposition and number of boreholes, including their orientation and depth, will become specifiable, given pathway and thermal constraints. Individual boreholes, likely at the guide hole stage, might be disqualified if structural geological conditions (joint sets, orientations…) are found to have a negative impact on pathway development probabilities.

The actual borehole orientation is controlled by first advancing a small diameter guide borehole, with a trajectory continuously or repeatedly verified by borehole survey data. After the guide hole is installed and all relevant data collected, the large diameter repository borehole will be advanced along the guide hole path with aid of a mandrel attached to the drill bit. During construction of either the guide hole or the repository borehole, it is possible for the drill path to deviate from the initial design profile (although extremely unlikely for the mandrel-guided drilling). Guide hole deviation can occur due to sub-surface characteristics (e.g. heterogeneity of the rock mass, structural features) or drilling issues (e.g. weight on bit, bottom-hole assembly composition). The magnitude and orientation of the deviation can result in issues associated with borehole repositories being closer together than initially intended or, in extreme scenarios, boreholes coming close to a pilot hole that was used for site qualification or that will be used for monitoring.

*Casing Failure*: In the base scenario that we propose, and for the DBP repository concept in general, we suggest that casings be limited to the upper part of each deep borehole to protect the zone where rock mass fractures are sufficiently open to allow flowing groundwater. We recommend this as well in the recognition that the natural rock mass at the chosen site, be it crystalline or sedimentary, is a highly resistant rock mass to geochemical perturbation, and is to be preferred as a resistant barrier in comparison to materials such as oilfield cement or steel.

Furthermore, in a repository site where there is a cover of weaker rocks, such as unconsolidated sands and clays covering an igneous rock mass, sustaining an open borehole will require the use of a casing, properly installed. We assume that the shallow conductor pipe protects the shallow surficial zone. Below this, we have recommended a 200 m deep surface casing minimum, and have even suggested that consideration be given to using casing that is geochemically more resistant than corrodible metals.

Hence, in some design scenarios, casing may be installed as a structural support and fluid isolation system in specific sections. It remains possible that the technical design of the DBP repository will involve much deeper surface casing placement, or that there will be another casing for the entirety of each borehole in the repository, or in some boreholes where conditions are deemed in need of additional casing. This means that the casing and its sealant with the rock mass is a barrier, and breaching that barrier may increase the risk of radionuclide escape.

The casing will be attached to the borehole wall by cement or other sealant if it is a permanent fixture of the DBP system. Casing failure can be caused by high in-situ stresses exceeding the strength of the casing and resulting in severe deformation or by failure of the cement-casing or cement-wall binding. Casing failure could be observed in isolated sections or the entire system depending on the severity. All casing failure scenarios will likely result in removal of the damaged section(s) as well as reinstalling of the casing. This will result in increased project costs with the requirement to purchase new casing equipment and time devoted to resolving the issue.

We perceive that the following issues present a risk that the casings are not satisfactory, or that the casings could become impaired during drilling and emplacement:

- Encountering of unexpectedly high stresses in the ground that allow some slip along favorably oriented planar discontinuities (faults, joints…).
- Inadequacy of the seal integrity behind the casing (between the borehole wall and the casing wall).

These casing risks can be mitigated by a number of assessments and analyses taken during the site qualification and drilling, and cases where concerns exist can be addressed:

- The combination of stress data and the orientation for the structural features will allow the probability of slip along favorably oriented planar features to be quantified in a probabilistic sense, and conservative design steps taken (including potential abandonment of a particular borehole, downgrading it to a low-level waste borehole because of perceived risk, altering the design trajectories, and so on).
- Once casing is in place, and the sealant set, while the casing is full of water, acoustic techniques can be used to evaluate the quality of the seal between the casing and the rock mass. Inadequate quality of seals can be identified in this QA/QC process.
- Multi-arm calipers can be used during the drilling of the large diameter deep borehole to precisely measure the rock wall geometry as well as the inner diameter of the casing to assure that it has not experienced significant deformation that would indicate slip of a feature in the rock mass or other casing deformation mechanism.
- Perforate-and-grout methods, preferably using resins, can be used to address poor seal quality.
- If approved, and likely to be much easier with polymeric casing instead of steel casing), the entire surface casing string can be removed before final backfilling, and the borehole rehabilitated with special grouting if needed.

It is our opinion that sufficient options exist to guarantee the integrity of the casing system as a barrier, ranging from replacing geochemically unstable cement use with better sealants, using fibre-reinforced epoxy casings, to replacement under unusual circumstances, downgrading borehole use, or abandonment and sealing. The many options available make the modular DBP repository concept more robust than a single mine concept, in our view.

### 6.2.2 Design and construction risk factors

Design and construction decisions are major factors influencing the overall post-closure safety of the DBP system. The decisions and activities undertaken directly contribute to the DBP systems' ability to isolate the radioactive waste and inhibit potential transit of radionuclides to the near-surface environment. A selection of design and construction elements is highlighted for discussion: these issues are dealt with elsewhere in the report, here we discuss them in the context of risk.

- Borehole geometry
- Use of casing
- Use of cement
- Drilling method
- Fracture remediation

- Selection of buffer materials
- Selection of upper sealing zone materials (hole backfill)

*Borehole Geometry*: The construction of a deep, large diameter borehole for the placement and isolation of nuclear waste will entail somewhat larger diameter boreholes than typically drilled in the oil and gas and the geothermal energy industries. Significant additional depth of the borehole or additional diameter moves the borehole from the realm of proven capabilities and into the realm of limited practical experience, except in cases in the mining industry, which are also limited.

It has been shown that the excavation damaged zone (EDZ) around a circular opening in rock is proportional to the excavation's diameter (among other factors such as tensile strength and construction method). So, for a large diameter borehole, there is a larger zone adjacent to the borehole that is damaged, in comparison to a small-diameter borehole. This damaged zone will likely have a higher permeability compared to its pre-damaged state, potentially allowing for easier transport of radionuclides in the region adjacent to the borehole. So as the borehole diameter is increased, the volume of higher permeability rock mass is also increased, resulting in some level of increase in the probability of flow of dissolved radionuclides in this region.

A factor coupled with diameter is the overall depth of the borehole. Deep boreholes have been drilled before (as discussed in chapter 2), but the final diameters of these boreholes usually are on the order of 150-350 mm, whereas we propose a diameter of 500-750 mm to accommodate high-level waste canisters of 400-600 mm diameter (all of these dimensions are hypothetical at this time). Machinery with high lifting and torque capacities will be required to operate drill tooling along with other down hole equipment at significant depth (several kilometers) for a large diameter hole. However, down to a depth of 1 km, we do not perceive this recommended diameter to present undefined risk.

The diameter and depth of the placement boreholes affect the damage around the borehole wall. The risks that this damaged zone becomes a pathway for radionuclides may be small, but it must be evaluated. Risk mitigation may involve several design decisions and actions, starting in the proposed test facility.

- Different design of large-diameter percussive drilling systems may lead to more or less damage to the borehole wall; this should be assessed, given different drill designs available. In the extreme, it may be decided to avoid percussive methods in favor of diamond drilling, if this is found to significantly improve wall conditions.
- The impact of damage on the borehole wall must be evaluated quantitatively. This is only realistically possible through the design of a downhole packer system deployed in the a DBP test facility (before site qualification), supported by seismo-acoustic logging methods.

- If it is deemed necessary to intercept the potential EDZ pathway, resin treatments, silicates, and other agents will have to be investigated for potential use on the borehole wall.
- Longer boreholes would lengthen radionuclide release pathways and reduce flow risk, so increasing the depth is an option. (Note that a longer casing will not impact the within-the-rock damaged zone pathway, therefore this is not a useful mitigation process for this case.)

At the present time, we are identifying this issue as worthy of assessment, but we believe that bit design and good drilling practice will result in a borehole with a damage zone that does not represent a significant pathway risk, considering the apertures of the induced microcracks. If this opinion is found to be incorrect, we also are of the opinion that borehole wall treatment processes exist or can be developed to reduce the viability of the pathway to negligible risk levels.

*Use of Casing*: This issue has been repeatedly raised and discussed in this report. To repeat the premise, typical casing for wells in the oil and gas industry or the geothermal energy industry are made of high-quality steel. The production lifespan of these wells is decades, considerably shorter than the vast length of time that is required to isolate nuclear waste until its radioactive level is low enough so that consequences of a breach are trivially small. Over this time span, the steel casing will corrode as it is not geochemically stable under the expected deep earth conditions. The corroded steel can result in a new pathway for the flow of radionuclides as a potential fissure or higher permeability zone between the casing cement and the buffer material forms.

- We recommend that the use of steel casing be restricted to the top of the boreholes (no deeper than the recommended 200 m surface casing), eliminated altogether (likely not feasible), removed before backfilling, or be substituted with a geologically stable reinforced polymer (e.g., carbon fibre-epoxy).
- If permanent metallic casing is deemed necessary for the surface casing interval, we recommend the use of highly corrosion resistant alloys, of which Hastelloy™ is one possibility.
- We are not concerned about steel used for the shallow conductor pipe (5-15 m). The upper part of the sealed and backfilled borehole, where it is adjacent to shallow subsurface sheeting joints and natural fractures, cannot be considered a long-term barrier in any case.

*Use of Cement to Secure Casing or as a Backfill Component*: Cement may potentially be utilized in the DBP system as the structural support fixing in place the casing to the borehole wall and providing a low-permeability seal of the annulus behind the casing. Cementitious products can also be used in some proportion in concrete to be used as a seal or cap in the engineered barrier system (no steel reinforcement). Depending in part on the composition of the concrete (aggregate material, cementing agent, additives), the long-term geochemical stability is in question. Once the cement begins to degrade, the structural support that it is designed to provide will diminish, but more importantly, the products of the cement degradation themselves may be less stable in the geochemical environment in the DBP repository rock mass, allowing permeability generation. For example, calcium carbonate ($CaCO_3$) and calcium sulphate ($CaSO_4$) are far more soluble than the natural silicates found in granites, quartzose sandstones, and shales.

Additives used to increase the ease of placement of concrete (sulfonate-based or carboxylate-based superplasticizers) and other compounds such as latex to reduce the cement (concrete) permeability have effects on the acidity of the aqueous phase, and these reactions may accelerate the degradation of the cementitious phase (García *et al*., 2018).

Degraded cement could result in the slow development of pathways allowing for the future flow of radionuclides along the borehole trajectory should sufficient downhole pressure build up from gas generation. If casing is deemed to not be required, then the use of cement as a structural component of the borehole supporting the casing can be wholly avoided. In this scenario, cement may be used as part of a sealing unit at various locations throughout the upper section of the borehole (discussed later).

The approaches to mitigation of long-term risks associated with the possible use of cementitious materials that are geochemically unstable are well understood, and include the following, amongst others.

- Develop alternative sealing, buffer, and backfill formulations that avoid the use of Portland-type cements altogether. If a binder is necessary, polymeric resins have extremely long potential lifespans in-situ if not exposed to ultraviolet radiation, ionizing radiation (close to source), or solvents. Carbon fiber as a reinforcement involves a geochemically inert material, and epoxy resistance to ionizing radiation can be guaranteed with the use of fillers (e.g., $TiO_2$).
- If cement is deemed necessary, for example in a concrete mix for a cap or seal, the mix should be carefully formulated with silica-based aggregates and sand of appropriate size ranges so that a dense concrete can be achieved with as little cement powder as feasible. This may involve a granular gradation ranging from silica flour in the 1-10 micron range, to coarse aggregate (5 mm) in the appropriate proportions, so that the fine-grained fractions occupy much of the pore space and reduce permeability accordingly. (Note that a concrete mix with extremely low cement content is more difficult to place because its flow characteristics and tendency to segregate present challenges).
- Using techniques mentioned in the point above, cementing formulations and concretes should be constituted so as not to shrink during set and long-term cure. This should be achieved mechanically as much as possible, avoiding all “chemical” solutions that purport

to overcome cement shrinkage. All of these agents are of questionable value for long-term geochemical behavior of cement and concrete formulations.

- Explore the range of available cementitious materials to determine the product that is the most stable geochemically, that will generate degradation products that are of low solubility, and that will not shrink during the slow degradation process.
- Avoid the use of aggregates and other concrete components that have any potential reactivity, such as chert, glassy slag, and other materials that will decompose or alter chemically during the repository functional lifespan.

We note that if the use of high-quality cement is limited to the sealing of the surface casing, and the remainder of the borehole does not have casing, an argument can be made that it is sufficient to use high-quality cement powders because the functional seals are those far closer to the canister placement locations in the boreholes. In other words, the critical seals, barriers, and cation adsorbents and migration retardants are those closest to the high-level wastes, not those that are distant. Of course, provision to entirely remove surface casings before final backfilling may be part of the DBP design.

*Fracture Sealing*: Drilling a deep borehole into any rock mass is likely to encounter fractures of various scales and conductivity. Even with a site qualification process that precludes repository sites with significant water-bearing conduits (i.e., fractured zones, faults, open joint sets, karst features…), smaller natural fractures will exist within the rock mass and intersect the borehole at depth. For this reason, all fractures encountered of a certain size (aperture, width) will be subjected to in-situ testing of hydraulic parameters to determine if remedial measures should be taken. It should be noted that not all fractures are fluid-bearing, (e.g., Abelin *et al*. 1991); an analysis of fractures at the Stripa test site in Sweden noted that there was a significant channeling of fluid flow in the few largest-aperture fractures, resulting in large portions of the fracture network being essentially dry. If the fracture is deemed to be significantly water-bearing, remedial actions could be undertaken after the fractures fluids are sampled and sent for analysis to determine their provenance. The goal of the remedial action is to provide a long-term, geochemically stable seal of the fracture in the borehole vicinity to improve the integrity of the backfilled borehole pathway against future significant flow events.

In a low porosity rock mass with natural fractures (granites, dense siliceous sediments…), the pathway development options are very few:

- Pathways that may develop through the system of natural fractures and other discontinuities in the rock mass;
- Pathways that may develop along the entry points, comprising the pilot holes for site qualification (and monitoring) and the placement boreholes, including any excavation damaged zone around the boreholes; and,

- Some combination of these two pathways (e.g., fracture flow connecting the placement borehole to another borehole or pilot hole).

The mitigation of escape risk and pathway development risk therefore must address in great detail the pathways that could possibly develop in the natural fractures in the rock mass. The nature of the pathway must also be assessed in terms of diffusion-dominated transport or advection-dominated transport (i.e., flow in fractures) and this diffusion/advection assessment impacts site qualifications (Avis and Kremer 2017). For the case of highly competent granite matrix that is impermeable, with extremely low diffusivity, the transport mechanism may well be advection only within the natural fractures; these fractured must therefore be tested for conductivity values down to some threshold value to quantify risk (probability of transport).

We note with respect to advective flux and potential transport of radionuclides that at depth in competent igneous rock masses (low fracture density, no tectonic perturbation) the vast majority of fractures are essentially non-conductive (i.e., functionally closed), or exhibit flow that is so slow as to be inconsequential. Furthermore, we note that as we go deeper into the earth, the salinity of the natural pore fluids increases, generating a highly stable density-stratified regime, where significant upward flow (against the density gradient) is essentially impossible. In such a case, although flow in a conductive fracture can occur, this flow is likely to be horizontal, along the density isobar, rather than upward against the density gradation.

Mitigation of risk associated with potential flow through conductive pathways in the rock mass may involve a number of options and processes.

- Identification of conductive fractures intersecting the guide holes (before the waste placement borehole is advanced) and quantifying the transmissivity using double packer flow tests or increased hydraulic head tests, all the while avoiding excess pressures that could negatively impact the fractures' apertures and thus the flow rates. This will help classify detected fractures in terms of pathway potential and lead to decisions about sealing conductive natural fractures.
- It is possible to inject material into natural fractures that are noted in the guide hole, but if the fractures are conductive, it will be best to develop a grouting system that can be operated in the 600 mm diameter borehole to assure sealing results (and test the results post-sealing).
- Research into past results and field experiments will help identify appropriate grouts and insure their geochemical stability.
- Ideal grouting materials will be of low viscosity, without particulate matter, silica mineral wetting, and still sealing if exposed to the small amounts of water present in natural fractures.

- To reduce or eliminate risks of making fractures more conductive, all sealing activity must take place at pressures substantially less that the minimum in-situ stress to avoid all possibility of hydraulically fracturing the natural fracture system and exacerbating outcomes.
- Post-grouting testing of the most conductive fractures is advised.
- It is technically feasible to place a setting membrane across a conductive zone using casing patching technology developed in the oil industry. An appropriate length section of a polymeric material is expanded against the zone, and setting triggered catalytically.

In extreme cases where the frequency and apertures of the fractures are deemed to be too severe and can be shown to be hydraulically connected to adjacent boreholes, the service level of the borehole can be changed to intermediate-level or low-level waste capsules only.

*Drilling Method*: A percussive drilling method is proposed as the main means of advancing both the guide holes and the large-diameter repository boreholes. Percussive drilling uses the rotary energy generated by the drill rig and the hydraulic energy of the drilling fluid to continuously raise and lower the drill bit to advance through the rock mass, while rotating so that the impact devices strike a new section of rock with each blow. Percussive drilling is less common than rotary drilling, where the drill bit uses exclusively a rotational action to cut through the rock. Percussive drilling has been shown to have higher rate of penetration (ROP) while resulting in very straight bores (Bruno, 2006). The same report also noted the limited use of percussive drilling in the oil and gas industry and some evidence that the excess vibration resulting in borehole stability issues in weak granular strata as potential drawbacks compared to rotary drilling.

The issue of generation of a damaged zone around the borehole was discussed above in the context of pathway development. To assess the risks of pathway development, we recommended exploring the permeability change in the damaged zone associated with percussive drilling, conventional rotary drilling, and with different bit types. If the damaged zone possesses negligible pathway potential with percussive drilling, we recommend staying with percussive drilling. If there is a substantive and important difference compared to rotary drilling, decisions will be undertaken to manage this risk through choice of a rotary drilling with appropriate drill bit design, or even beneficiation of the borehole wall through some form of additional damage sealant.

*Selection of Buffer Material*: Buffer material provides both mechanical support for the waste canister in the repository and acts as the first barrier once radionuclides escape from the waste canisters. Various conceptual designs for the placement and long-term isolation of nuclear waste have proposed different buffer materials; perhaps the main candidate material is bentonite (an extremely absorbent smectite clay based natural material); however, other alternatives have been proposed, and are mentioned elsewhere in this report. The key considerations when selecting a buffer material are its cation exchange capacity, its ductility and resistance to any shrinkage, its permeability to aqueous solutions, its thermal conductivity (wet and dry) and its long-term geochemical stability such that it can perform its long-term barrier and support functions indefinitely. If the buffer material degrades or undergoes volume changes, regions of high permeability can develop.

Part of the research associated with the DBP repository design will be choice of an appropriate buffer material and a methodology to place the buffer material completely around the canister once it is in place. This is one of the reasons that bentonite (smectite) is widely recommended as a sealant. It swells dramatically in contact with fresh water, but far less in contact with salt water or $CaCl_2$-based water (both common at depth in crystalline rock masses).

Risk mitigation in the choice of buffer material and buffer placement around the canisters to generate a long-term effective seal will require some research and field experiments.

- Buffer material placement geometry (length of buffer material above and below the canister, the annular thickness around the canister...) must be decided in terms of risk reduction through adsorption of cationic (metallic) radionuclides ($^{90}Sr$, $^{137}C$, $^{60}Co$, etc.) that probabilistically might escape from a breached (failed) canister.
- Even canister design must be guided in part by the placement method for the buffer material. For example, a canister with a flat bottom will be easier to seal against the buffer material below it than a canister with a rounded bottom.
- Buffer material should be of exceedingly low permeability, be ductile and retain ductility indefinitely, be insensitive to the temperature changes that will be encountered in the near-canister environment, retain cation adsorption capacity in the long term, and be otherwise geochemically stable.
- Because buffer material will be exposed to the highest level of radioactivity (gamma radiation) emanating from the canisters, it must be immune to damage from ionizing radiation at the levels predicted.
- Smectitic clays found in bentonites swell in the presence of water, and this will be a considerable asset in forming a seal. However, the swelling potential of smectite is greatly reduced in the presence of NaCl brine, and even more so in the presence of divalent cation brines (e.g., $MgCl_2$, $CaCl_2$). Conservatively, an alteration of the pore water chemistry to divalent cations cannot be ruled out, therefore:
    - The behavior of buffer materials in the presence of saline groundwaters and divalent cation salts must be investigated carefully.
- Although mixes can be envisioned (e.g., 5 mm pressed pellets of dry smectite clay and 50% silica flour), the swelling behavior and thus sealing capacity against the canister must be clearly quantified in the context of the DBP repository geometry.

- There must be no chance of shrinking of the buffer material in the distant future to avoid the opening of a tensile crack that could serve as a pathway. This shrinking can be mechanical in nature (syneresis), chemical in nature (change in the exchangeable cations), thermally induced (dehydration), or stress-change-induced (a high stress following by a diminution of stress leading to cracking).
- There must be no corrosion reaction with the exterior metal cladding of the canister, and no reactions with the materials inside the canister that could become exposed if there is a canister failure.

*Selection of Upper Sealing and Backfill Materials*: We envision a sealing strategy that will involve a sealant placed between each pair of high-level waste canisters in a placement borehole, combined with a more substantial (longer) sealant zone placed above the array of canisters, below the backfill zone. Conceivably, there could also be sealant zones placed in the upper part of the boreholes in a sandwich strategy, if deemed appropriate. Figure 6-2 shows the concept for the canisters themselves: the buffer material is itself a sealant, but another different sealing material is advised as an impermeable, zero-porosity, geochemically stable sealant separating each pair of canisters. Although we recommend asphalt, it is feasible that other effective sealants could be used. It is also possible that a solid bridge plug seal made of polymeric material is used as a mechanical seal.

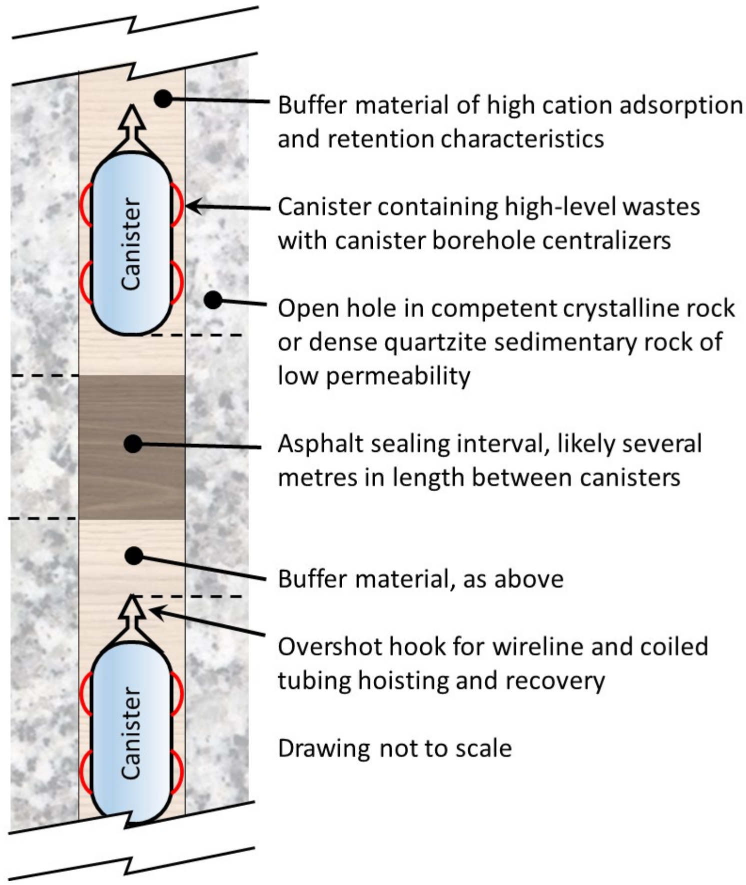


*Figure 6-2: Schematic of canisters and repository section barriers*

The upper sealing zone, the "master seal", is located immediately above the HLW canister repository section of the borehole, for some distance above the top canister, to divide the borehole into two distinct sections, with the backfill material placed above the master seal. Above the master seal will be a series of plugs, seals, and backfill mixtures extending to the top of the borehole to act as a last set of barriers to radionuclides migrating within the borehole and moving toward the near-surface environment.

Then, a formulation for the backfill material must be chosen; different compositions of materials and systems of plugs have been hypothesized and utilized in conceptual sealing plans for deep boreholes. Some of these materials include cement, bentonite, backfill of crushed sand and cement, or compacted graded drill cuttings. Mechanical or inflatable packers, bridge plugs, and other mechanical seals can be implemented if deemed necessary and if sufficiently stable for the repository lifespan. If any of the materials selected is not suited to the conditions it will be exposed to at depth, rapid degradation could occur, allowing for the facilitated movement of any released radionuclides.

However, it is important to note that distant barriers are far less important than proximal barriers. In other words, the backfill material in the upper 500 m is not the most critical seal, it is the buffer and sealant materials in the canister emplacement section. If the latter are ineffective, then a considerable length of borehole will be involved, and many natural fractures intersected, and the efficacy of a backfill material in the upper half of the borehole is perhaps moot.

The risk mitigation procedures for the selection of sealants, mechanical bridge plugs, inflatable permanent packers, and backfill material involve assessing placement reliability, physical properties, and geochemical resistance. These have been mentioned in sections above, and will not be repeated here. These procedures, materials, and operations must be tested in a DBP Test Facility (Appendix I) before site qualification and site development.

## 6.3 First order operations risks

This section focuses on risk events and risk factors that could occur after completion of construction and up until the final closure of the borehole. Discussion of risk factors that stem from operational tasks, but impact the post-closure safety, are noted, but more thoroughly discussed in later sections.

Pre-closure risk assessments have been undertaken by Sandia National Labs in the United States as part of the Deep Borehole Field Test (DBFT) project (Hardin *et al.*, 2019). This assessment reviewed every step of the operations process (from qualifying the borehole after construction up until the final sealing of the borehole). It is assumed that the process reviewed by Sandia National Labs is similar to the process that will be followed if the DBP repository system is adopted. An overview of the risk events highlighted in the above-mentioned report are summarized in the following sub-sections. These sub-sections are divided into different operational steps that each comprise unique risk events and factors. A discussion is provided at the end of the section to discuss the potential risk associated with the events described.

### 6.3.1 Site design for risk minimization

Once construction is completed, the borehole may be approved and begin receiving waste for placement, isolation, and long-term residence. During this process, canisters containing radioactive material are actively being moved at the repository site and handled by personnel and machinery. This presents the potential for events that could result in the exposure of workers and the near surface environment to hazardous quantities of radioactive material.

However, one great advantage of the DBP repository concept is that it is far more resilient to construction accidents and unforeseen events than a mine repository. For example, the accidental breaching of a canister in a mine during transit in the shaft or on the roadways to the placement site incapacitates the entire mine, or a large portion of it, until the issue is resolved to the satisfaction of the safety personnel. There may be only one pathway to the site of the breached canister, restricting actions available to address the clean-up and transport of the radioactive material. If remote-control devices to handle the actions are needed, these may not be possible by “line-of-sight” control (direct visual contact), only by cameras, which may not be optimally located. The ventilation system in a mine is designed to move air efficiently in one direction, and this may further impair efforts to rectify the situation. Once the material is recovered and available for transport again, it will have to be moved out of the mine via the roadways and shaft, and the attendant probabilities of an event are much larger because the system was not designed for that process.

In contrast, at a DBP repository site, the access design is such that there are always several ways to approach a given location, and ventilation is not a constraint. Line-of-sight semi-robotic control remains straightforward, and clean-up options exist that are not available to an underground repository. Figure 6-3 shows a design concept that allows full access to all boreholes from all directions; large equipment moves exclusively on the outer road, whereas small vehicles move on the inner road. The outer road surface is 20 m wide, allowing maneuvering of wireline units, coiled tubing units, drilling rigs, and other large systems. The inner road surface is for service vehicles, personnel vehicles, foot traffic, QA/QC management, and other smaller-scale traffic such as forklifts, coffee delivery, and other critical functions.

Because the DBP repository concept is on the surface, and because the canister placement is taking place in only one borehole at a time, there is never more than one high-level waste canister on the site at any time, delivered when needed from a more distant mobilization area. That canister is placed, buffer material is placed, the sealant is placed, another layer of buffer material is placed, and the procedure repeated, while QA/QC criteria are met at every step of the process. Hence, any accident during placement can only involve one canister and one borehole, eliminating risks associated with the potential for multi-canister accidents on the DBP repository working site.

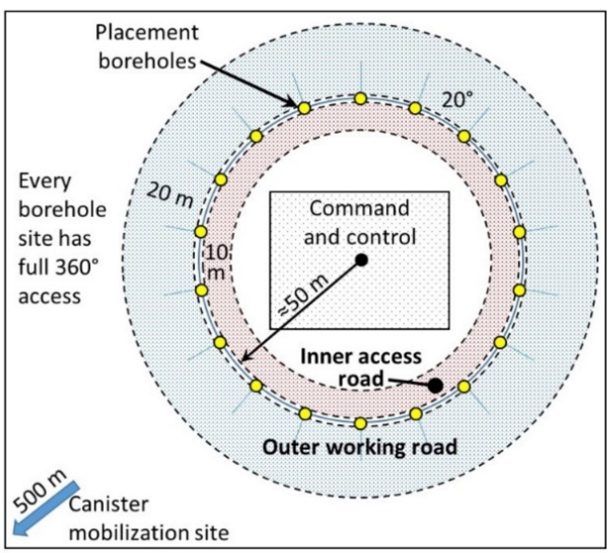


*Figure 6-3:* A surface design scenario for wellbore access

We also note that the placement operation involves one borehole at a time; that borehole is active until the master seal is placed in the borehole above the last canister interval. Backfill placement may also be completed before moving to another placement borehole for canister placement. This means that a DBP borehole comprises one module that is sealed and isolated before another module (borehole) is activated for canister placement. We believe that this modularity gives more flexibility to an operational plan and potential disruptions to the plan than a mine repository, which is severely constrained operationally in several access aspects (single shaft, limited numbers of tunnels…). We believe that the DBP repository concept is also more resilient than a mine in terms of disruptions and potential changes that may happen during the course of waste isolation activities: an accident at a DBP repository will involve one hole; in a mine repository, it could impair the entire facility, and the huge cost of the mine put at risk.

### 6.3.2 Borehole qualification

During borehole qualification for each individual repository borehole that will receive high-level waste canisters, there is a clear two-stage process. First, the guide holes are fully logged, tested and analyzed to identify all important features that could impact the use of the large borehole for waste placement; in other words, this is a decision-making process using a risk-based set of metrics that will be set during the repository design process. At this point, a decision is made, on a case-by-case basis, for one of the following options:

- The borehole will be expanded to full diameter (and then requalified) for waste canister placement.
- Issues have been identified that suggest that the borehole should be drilled, but likely will be downgraded to accept intermediate- or low-level waste capsules.
- Issues of greater concern have been identified, and the borehole should be drilled, but limited to placement of low-level waste capsules.
- The risks of using a full-diameter borehole in these conditions are significant enough that the guide hole should be sealed and abandoned.

The large-diameter borehole is then advanced to the design depth, and it is also checked and evaluated for its suitability to house nuclear waste. This involves lowering an assembly of wireline tools or drill-string tools for qualification and measurements. Once again, the decisions listed above can be taken: suitable for high-level waste, suitable for lower grade waste capsules, or sealed and abandoned.

Re-qualification procedures may also be repeated if concerns arise at any time after the placement and sealing of each waste canister. This may be done to ensure that during emplacement the borehole wall or engineered barrier system has not been damaged by either the emplacement equipment or the waste canisters, or to check again the results from the guide hole qualification and the full borehole qualification mentioned above.

We note that by the time a placement borehole has reached this stage, it has undergone multiple re-assessments and re-qualifications. First, at the scale of reconnaissance geology and geophysics involved in site selection; second, at the scale of the site itself during site qualification; third, at the local borehole scale through the guide hole qualification; and fourth, the final qualification of the placement borehole itself. At any point in this process decisions can be made. As previously mentioned, this is in the spirit of engineering adaptive management of a process: keep learning and collecting information to guide further decisions.

We also note that during the qualification processes outlined above, actions are all prior to any waste being placed at the bottom of the borehole, so there is no potential for the qualification tooling and procedures to impact waste canisters in any way. No canister breaching can take place, no radionuclides escape, no potential contamination of the equipment can occur before the full qualification has been done. However, the following issues may arise:

- A small block of rock may loosen and fall from the borehole wall, leading to borehole blockage and a need for clearing and re-assessment of borehole integrity.
- Tooling impacting the borehole wall resulting in structural damage (to the surface casing, to the rock mass, or to any component of the engineered barrier system);
- Tooling retraction failing and equipment is stuck downhole; and,
- Tooling components breaking off and falling into the canister repository zone during the canister placement operation.

These events are to be largely avoided by appropriate operational management and adequate equipment deployment, but incidents can happen, as in conventional O&G drilling. If tools are stuck in the hole or fall downhole, there are systems for retrieval (“fishing” tools) that are well-developed in the O&G industry, so we consider these risks to be manageable with the only consequence being operational delays. In an extreme case, if necessary, a borehole can be abandoned, or the bottom (where the abandoned tool may be) is sealed and canisters still placed above, or the borehole downgraded to a lower level of waste placement.

For the case where qualification is completed, but after or during the placement of waste canisters, the following issues may arise, including those mentioned above in the pre-waste placement borehole qualification phase:

- Tooling impacting buffer material, sealant or mechanical bridge plug resulting in damage or integrity impairment; and,
- Tooling impacting canister resulting in damage or rupture.

Risk reduction measures for this stage of operations include a number of actions, and the processes listed below will apply to most of the subsequent sections (and thus will not be repeated):

- Repeated dummy practices are required so that crews will have encountered all actions and processes many times before actually handling a high-level waste canister.
- Establish and maintaining a high level of equipment maintenance with stipulated checks by operating crews regularly (daily at least) and occasional checks by the site safety personnel, with images, measurements, and checklist records recorded for each activity.
- Establishment of second-level backup safety systems, such as a small auxiliary steel wire cable to carry a tool if it becomes disengaged from the wireline or coiled tubing downhole system. A careful study of the equipment commissioned or purchased for the placement of canisters will permit the identification and installation of auxiliary safety back-up devices and procedures.
- No untethered tools (wrenches, steel goods) should be allowed near any open hole to avoid the chance of tool loss downhole. Tool counts and numbering are established to avoid misplacements and loss.
- Establishment of a double personnel verification process, where actions are verified by a second team member at all times while handling canisters or placing buffer, plugs and sealants.
- All operations deemed critical (such as canister attachment to the wireline yoke, lowering the canister downhole, activating the centralizers, un-yoking, and returning the yoke to surface) are to be televised continuously.
- If uncertainties, hesitations or issues arise, the television record and personnel inputs are studied to allow for continuous improvement.
- Incident reporting is necessary, and a protocol is necessary for various types of incidents, with a methodology for recommending and implementing improvements.
- No borehole that presents a significant chance of loose rock falling should be qualified for high level waste placement.

During canister placement and sealing operations, the system should resemble the procedures in an operating room: highly trained attendees, full documentation, redundancy and back-up, double verification of actions, counting of instruments, and continuous improvement. This is the most powerful approach to risk mitigation during all operations.

### 6.3.3 Waste receipt and on-site transfer

Waste packages are assumed to be received from a remote off-site location (where canisters are assembled), temporarily stored near the DBP repository head site, then individually transferred to the head of the active repository borehole for placement and long-term isolation. In Hardin *et al*., (2019), this is discussed as four different processes, each with a sub-list of activities. As the risk events are similar enough during all these separate phases, a condensed list of risk events is provided (this list can be extended and greatly detailed during the planning process):

- Machinery transferring canister breaks/malfunctions;
- Machinery transferring canister is improperly set-up (i.e., shielding or redundant systems not properly in place);
- Canister is dropped or otherwise damaged during receipt or transfer; and,
- Canister collides with equipment during receipt or transfer with no visible damage, but concern about integrity.

As in the risk mitigation list in the previous section, many steps can be taken to reduce risk. These will not be addressed in detail because the specifics of the handling process remain undetermined at present. It is sufficient to say that we strongly recommend that each high-level waste canister should be maintained in an appropriate protective sheath until it is ready to be lowered downhole. If the canister design is deemed in any way breachable during operations, we further recommend that the canister system be enhanced by enclosing each entire canister in a reinforced polymeric encasement (e.g. 25 mm thick carbon-fibre/epoxy) to reduce risk.

#### 6.3.4 Waste emplacement and retrieval

The waste emplacement stage begins with the attachment of the waste canister to the emplacement system (wireline yoke, drill string yoke, etc.) until the tooling is released from the canister and withdrawn from the borehole. During this phase of operations, the following risk events are possible:

- Canister arrives improperly equipped (e.g., without a harness and centralizers and the system to activate the centralizers at depth);
- Canister damaged during attachment to emplacement equipment;
- Shielding surrounding the canister is noted to be improperly set-up or damaged prior to emplacement;
- Canister dropped down borehole from surface;
- Canister dropped during lowering down the borehole;
- During emplacement, canister impacts obstruction that has developed in the borehole (e.g., unanticipated loose rock block obstructs part of the hole);
- Canister becomes stuck in the hole above the intended placement location; and,
- Emplacement equipment such as the centralizer activation or the yoke release system malfunctions downhole with or without canister attached.

- Tooling involved in the hoisting system is accidentally released and falls down the borehole and impacts the emplaced canister directly.

If a sealed canister is required to be retrieved, a procedure similar to emplacement will likely be followed (e.g., remove overlying sealant and buffer using water jetting system, reattachment of a weighted yoke to the canister hook, slowly raising to surface…). Any risk event that could occur during emplacement listed above has potential to also occur during retrieval. However, if the reason for retrieval is due to canister damage, the severity of any of the above events will be amplified due to the potential exposure to radionuclides.

Risk mitigation actions for these procedures will be studied and detailed when the FEED process (Section 7.3) is underway, and all actions will have been extensively studied and optimized at the DBP Test Facility (see Appendix I)

### 6.3.5 Setting intermediate plugs

Intermediate plugs may be set at various intervals to aid in the sealing of the borehole as well as to aid in transferring the vertical load of the canisters to the borehole wall (frictional load transfer, which occurs naturally). This process limits the stress concentrations on the lower canister shells, but care must be paid to the nature of the buffer material and the sealant. If the buffer material and the sealant both behave in a viscous manner, then frictional load transfer will decay, and there may arise higher loads applied vertically to the canister. This may require the incorporation of a frictional material section in the inter-canister region, such as a polymeric mechanical bridge plug (carbon fibre-epoxy mechanically set bridge plug), or a frictional material such as a 4-5 m long section of well-graded densified cuttings backfill, shown in Figure 6-4.

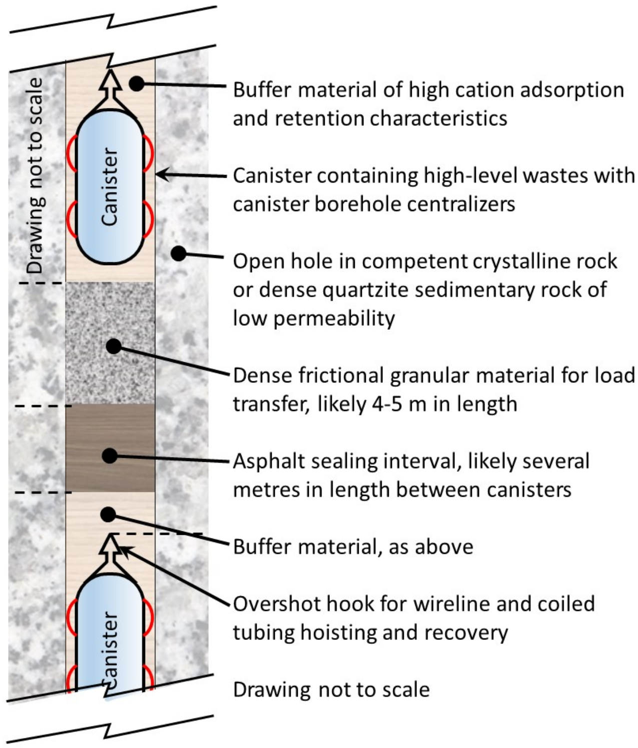


*Figure 6-4:* Inclusion of a dense frictional material ensures load transfer, protecting canisters

The intermediate mechanical bridge plugs will likely be lowered by similar equipment (with some modified tooling) used to emplace the waste canisters. The following risk events are possible during this stage:

- Mechanical bridge plug fails to set properly against the borehole wall, resulting in some probability of excess loading on canister;
- Plug array or the downhole tooling dropped, damaging canister or impairing the integrity of the buffer material;
- Plug and tooling malfunctions down the borehole and fails to retract properly, requiring removal; and,
- Plug and tooling component breaks off and is stuck permanently in the repository borehole through failure of retrieval attempts.

The reduction of risks (i.e., probability of such events) will be addressed in the design, and repeated testing and practicing of canister placement and sealing that will take place before actual canisters are isolated in the DBP repository should occur at the DBP Test Facility, which has now become a training facility. Because all mechanical bridge plugs to be used are to be made of polymeric materials or other "drillable" materials, a malfunctioning mechanical bridge plug can be removed and replaced (albeit not a desirable operation).

In addition to failure events, poor design, or incorrect/poor-quality of placement of intermediate plugs can have a long-term impact on the post-closure safety of the project. This will be discussed in section 6.4.

### 6.3.6 Borehole closure

After the last high-level waste canister is emplaced and the master seal installed, the upper part of the borehole is ready for final closure. It is not in the scope of this report to develop a full conceptual design of the system of plugs, seals, and backfill that will extend from above the top of the repository section to the surface of the borehole. However, based on a generic system of seals, plugs, and backfill, the following risk events are possible during this phase:

- Closure seals/plugs improperly placed, resulting in a higher potential for pathway development;
- Closure material dropped accidentally or in an uncontrolled manner, damaging existing borehole structure (e.g. surface casing interval or a borehole patch placed across a fractured zone);
- Closure tooling is lowered or raised too quickly, impacting or damaging and engineered barriers;
- Closure tooling malfunctions down borehole and fails to retract; and
- Closure tooling component breaks off and is stuck above repository.

Similar to intermediate plugs, poor design and/or incorrect/poor-quality of placement can lead to long-term impacts on the post closure safety of the project. This will be discussed in more detail in section 6.4.

### 6.3.7 Discussion of operations risks

The operational risk events discussed fall under three major categories:

- Issues resulting in project delays and economic loss;
- Issues resulting in immediate exposure risk for human operators and near surface environment; and,
- Issues resulting in increased post-closure safety concerns.

Issues resulting in project delays include those where tooling malfunctions or becomes stuck down hole. Potential examples will be found during all phases of the operations where equipment is utilized downhole for whatever reason. These malfunctions or accidents cause project operations to halt while the issue is resolved. Economic losses are incurred as the scheduled operations can not proceed and personnel and equipment are put on standby until the problem is resolved.

Issues resulting in immediate exposure risk for operators and the near surface environment occur when a waste canister becomes damaged on site resulting in the immediate breach of radioactive waste. This can occur at any point during operations where either waste canisters are being handled by personnel, or machinery or machinery is being operated near waste canisters (downhole or at ground surface). A downhole breach of a canister can result in contamination of the emplacement equipment and any other downhole equipment exposed. All contaminated equipment would have to be cleaned, inspected, and re-certified prior to returning to operational status. All contaminated material retrieved from downhole or from a surface clean-up will have to be properly stored and isolated at the surface for off-site transport (on-site repackaging of high-level waste is not an option).

Issues resulting in increased post-closure safety concerns include any instance in which the engineered or natural barrier system is damaged. This can occur at any point in operations where equipment can come into contact with constructed or natural barriers or during the construction of any barrier systems. Section 6.4 discusses more thoroughly how operational induced issues impact the post-closure safety of the repository.

## 6.4 First order post-closure risks

The most vital aspect of the repository is to isolate the nuclear waste for the design life chosen. A performance assessment must be undertaken to evaluate the DBP repository's abilities under a variety of scenarios to determine if the designed repository is able to meet the requirements set forth by the waste management organization, regulatory body, and technical repository committee. These "performance assessments", "post-closure safety analysis", or "safety cases", have been undertaken by different organizations at the conceptual level for various designs of repositories and are considered a necessary function during the pre-FEED and FEED stages of a repository project. Sandia National Labs in the United States developed a conceptual post-closure performance analysis for a 5 km deep borehole (Freeze *et al*., 2016). Deep Isolation, an American-based company working on developing a deep horizontal borehole solution for the placement and long-term residence of nuclear waste, has also released numerical simulations to back up a "generic post-closure safety analysis" (Deep Isolation Inc., 2020). The Nuclear Waste Management Organization in Canada (e.g., NWMO (2017), and many documents available online[56]) deal extensively with scenarios and analysis in their studies, although not of repositories of the DBP type.

We provide an overview of key risk features, events, and processes (FEPs) that may require consideration in a future post-closure analysis. This section will highlight major FEPs that have been considered in other post-closure assessments (i.e., Freeze *et al*., 2016; Deep Isolation Inc., 2020). A complete list of FEPs is provided by the Nuclear Energy Agency (NEA), a specialized

[56] https://www.nwmo.ca/

agency of the Organization for Economic Co-operation and Development (OECD). It is available in an online database[57] or in report format (Capouet *et al.*, 2019).

The following sections are divided into three cases: undisturbed repository risk, defective engineered barriers risk, and disturbed repository risk. Detailed definitions of these cases and the scenarios considered are provided in each sub-section. Each section will outline how the scenarios within each case affect the ability of the DBP system to isolate nuclear waste and inhibit the flow of radionuclides to the near surface environment. More detailed analysis of these issues is reserved for the future in the DBP repository activity progress.

### 6.4.1 Undisturbed repository risk

The undisturbed repository scenarios are the base scenario of the post-closure safety analysis. In the base case, a best guess is made (perhaps using the method of expert elicitation), or a probabilistic approximation is applied to the performance of the actual repository components with no major system failures or major events resulting in major changes to natural or engineered barrier parameters. In the undisturbed scenario, it is envisioned that the flow of radionuclides can occur through three potential pathways once the waste canisters have lost its ability to function as a barrier:

- Transport of radionuclides through the buffer, sealant, and backfill materials within the constructed borehole itself or through an adjacent borehole connected by a flow zone, or through any holes drilled for site qualifications, monitoring, guiding, and subsequently sealed and abandoned;
- Transport of radionuclides in an excavation damaged zone generated during the drilling of the waste placement borehole and residing as an annular zone of different transport properties than the rock mass; and,
- Transport of radionuclides through the surrounding rock mass, meaning transport through the natural fracture systems for a qualified site (one may assume that an element of site qualification is that the rock matrix is functionally impermeable to aqueous dissolved cations or gases because of pore sizes, capillary exclusion, density barriers, etc.).

Although the latter of these three scenarios is likely to be the pathway of most concern, it should be noted that it is possible for a combination of flow paths to exist; e.g., the radionuclides initially flow through the constructed borehole and then primarily are transported through the excavation damage zone, or along a natural fracture to another borehole, among other possibilities. For simplicity, single pathway transport mechanisms will be discussed with additional commentary provided, as necessary. Because a site will be in a groundwater recharge area, the only upward flow inducing mechanism though the constructed borehole and even into

[57] http://www.oecd-nea.org/fepdb

the rock mass seems to be the buoyancy associated with the possible presence of free gas in the water phase generated as the result of radiochemical reactions in the canister region.

*Transport of Radionuclides Through the Constructed Borehole*: The transport of radionuclides through the constructed borehole is defined as the movement of radionuclides via groundwater or gas through the regions excavated during the construction of the borehole. This region is divided into two major sections: the repository section (filled with waste canisters, buffer material, sealants, intermediate plugs and a master seal) and the upper sealed zone (filled with backfill, plugs, and seals). These two sections are assumed to be separated by a master seal at the top of the repository section.

Once the radionuclides escape from the waste canister, their flow path will be upward through the buffer material (likely through channels in the buffer material) and intermediate plugs of the repository section. The flow of radionuclides will then move up the borehole through the master seal separating the repository and upper sealing zone. The final flow path will be through the backfill, plugs, and seals of the upper sealed zone until it reaches the near surface environment.

We believe, for many of the reasons stated elsewhere in this report, that the probability of pathway development through the engineered and geochemically stable barriers within the borehole is functionally zero, given good quality placement. We believe that a more likely pathway, still highly improbable, is the escape from the canisters into an adjacent natural fracture system that is more distantly (down gradient) connected to a lower elevation feature that permits slow upward flow (discharge). In a site characterized by recharge, local upward flow is only possible through gas buoyancy effects or through changes in the elevation heads. The former appears to be a remote possibility, the latter is unrealistic. Nonetheless, there exist many natural barriers to this possible pathway as well. Risk mitigation measures related to this have been discussed previously, but it appears that a key factor is the identification and amelioration of the state of natural fractures intersecting the placement borehole. Hence, in sections above, the careful qualification of each borehole and the potential use of sealing materials of various kinds (borehole wall polymer patches, low-viscosity resin injection…) were invoked as possible means or reducing the probability that a flow path could be so generated.

We re-emphasize that many natural barriers that resist the possible flow to surface still exist even if a pathway develops, including fluid density effects, tight natural fractures, impairment of ionic transport through some adsorption, etc.

*Transport of Radionuclides Through the Excavation Damage Zone*: The transport of radionuclides through the excavated damage zone (EDZ) is defined as the movement of radionuclides via groundwater or gas through the region of rock immediately adjacent to the borehole excavation that was damaged during drilling activities. As discussed earlier, the excavation of a rock mass results in a zone surrounding the excavated region that is damaged. This damaged zone may have a prevalent microfracture pattern which can result in a higher permeability allowing for some flow of radionuclides to the near surface environment. It is assumed that the excavation damage zone is likely to exist for the entire length of the borehole. However, the connection and extent of the EDZ to other pathways (natural fractures) is likely to vary with depth because under the effects of stresses, both in the rock mass and in the wall of the borehole, natural fractures at depth are less likely to be significant flow paths. Many of the natural fractures may be deemed as closed, and the thermohydromechanical conditions after canister isolation are modeled and studied carefully to make sure that no mechanisms exist or will occur that could change this condition (e.g., generation of strong temperature gradients over a short time period).

Once the radionuclides escape the waste canister, the travel path will be first through the adjacent buffer material around the waste canister and then into the borehole wall. The radionuclides will then primarily flow via the EDZ in the near borehole wall rock mass to the near surface environment, or as detailed above, into a natural fracture zone that intersects an adjacent borehole.

We recommend that part of the DBP Test Facility research evaluation be the quantification of the extent and properties of the EDZ in practice, as the theoretical basis for making permeability predictions is weak. There are many ways of doing this, including precision flow tests, closely focused seismic methods, circumferential surface strain wave generation and attenuation measurements, tracer methods followed by borehole wall small-scale cores (20 mm diameter, 200 mm deep), and so on.

*Transport of Radionuclides Through the Surrounding Rocks*: The transport of radionuclides through the surrounding rocks is defined as the movement of radionuclides via groundwater or gas through the host rock and the overlying rock units excluding the portion of rock mass damaged during excavation (EDZ). This transport mechanism can involve the movement of radionuclides through either the rock masses' matrix by diffusion or through existing fractures/faults in the host rock and the above rock units. Diffusive transport through intact crystalline rock matrix is so small that it can be set aside as a reasonable mechanism for radionuclide escape at any rate that would be problematic.

Similar to the flow path noted for the EDZ flow mechanism, the radionuclides will first flow from the waste canister and through the adjacent buffer material to the borehole wall. The radionuclides will then flow into the undisturbed region of the rock mass via the EDZ. Once into the undisturbed rock mass, the radionuclides may be transported only through existing fractures within the host rock and overlying rock units. This flow path terminates with the radionuclides reaching the near surface environment in the host rock or overburden, or through intersection with another wellbore that has a potential flow path.

Matrix flow is not the issue in the chosen site because qualification depends on the existence of a low permeability rock matrix. Flow through natural fractures (or bedding planes or ancient fault traces, etc.) is the issue. The risk of such flow will be mitigated in the following way:

- First, a major element of site qualification will be selection of a site that has a low level of natural fracturing and other potential flow features.
- Second, site qualification will entail mapping the conductivity of natural fractures with depth to assure that appropriate repository depths are chosen so that the natural fractures are largely closed.
- Third, intersection of natural fractures with a placement borehole and the aperture (conductivity) of those natural fractures will be an element of borehole qualification.
    - All zones of appreciable conductivity will be ameliorated through grouting with a non-particulate grout or patched with a borehole wall polymer patch, or,
    - The borehole can be downgraded to intermediate- or low-level waste, or sealed and abandoned.

We believe these measures, in combination with the natural barriers to upward flow at a properly qualified site characterized by groundwater recharge, will reduce the risk of pathway development to a low value, and thereby reduce the potential human dose exposure level to radioactivity accordingly. In other words, if a pathway does develop that overcomes all of the engineered and natural barriers, it remains highly probable that the flow rate in this pathway is exceedingly small, so that:

- Dispersion and dilution take place during transit, reducing the level of concentration of radionuclides;
- Some retardation takes place, slowing the transit time of dissolved species; and,
- At the surface, because of the two previous mechanisms, the concentration of any excaping radionuclides will be small and the rate will be slow; dilution and dispersion through surface processes (precipitation, wind) reduce risks to inconsequential levels.

All of these processes, relevant to this section and above, must be subject to probabilistic analysis and risk assessment.

### 6.4.2 Damaged engineered barrier system risk

The engineered barrier system is a key element of the overall safety performance of the DBP system. A failure of one element or multiple elements of the engineered barrier system jeopardizes the ability of the system to isolate the nuclear waste. Different scenarios need to be considered to demonstrate the safety of the overall system under reasonable defect scenarios. Potential scenarios to consider include:

- Defective waste canister(s);
- Defective buffer material, sealants, intermediate mechanical or frictional material plugs;
- Defective master seal interval; and,

- Defective upper borehole sealing and backfill system components.

The defects listed could be a result of several processes. As outlined in section 6.3, it is possible that due to the placement methodology, or unintended impact between tooling and the engineered barrier system (e.g. collision between placement tooling and canister) integrity is somewhat impaired. It is also possible that the manufacturing process and quality control and quality assurance failed to detect an issue with a portion of the engineered barrier system within the canister itself, resulting in a sub-standard set of canister barriers.

*Defective Waste Canister(s)*: The waste canisters will be designed to prevent the escape of radionuclides from the encapsulated waste for an extended period of time after emplacement during the time of high radioactivity, and the temperature peak and attenuation. This amount of time is repository design dependent and not stipulated here. If the canister is damaged prior to, during, or after emplacement, or if the canister was manufactured to be sub-standard, it is possible that the release of radionuclides can occur prior to the expected time of release for an at-standard canister. Risk mitigation procedures and management methods mentioned above are to be put into place to reduce these risks. At all times before final hoisting on the wireline placement system for lowering, the canister must be encased in a protective sheath, even if this is simply an expanded polystyrene (Styrofoam™) sheath within a robust wooden crate. We presume that the manufacturers of the canisters will design an encasement that is capable of protecting canisters if impacted or dropped, and that can be easily removed when the canister is ready for lowering. We also assume that the canisters will arrive at the placement borehole head equipped with the centralizers and the harness-and-hook system by which they will be lowered to the downhole placement location.

As there will be up to 100s of canisters to be emplaced in a repository, there are scenarios that could develop based on the number of canisters that are defective (one vs. multiple) and position of the defective canister(s) (top versus bottom of the repository). Although this of itself is beyond the remit of this report, the multiple buffer-sealant-plug-backfill approach, coupled with the rigorous qualification process for each placement borehole and the natural barriers to upward flow, will give low probabilities of escape even with an undetected defective or damaged canister.

Even if all canisters should “fail” in a short time after placement and sealing, a properly qualified site with carefully qualified individual boreholes and appropriately placed buffer/seal/plug backfill systems will have flow levels so minute that the probability of significant human doses developing at the surface remain extremely low (Deep Isolation 2020).

*Defective Buffer Material and Intermediate Plugs*: The buffer material, sealants and intermediate mechanical or frictional material plugs are the first line of engineered barrier systems if the radionuclides breach from a defective or damaged waste canister. They also provide mechanical support and stabilization to the waste canisters to ensure high stresses are not carried by the waste canister shell. The designed systems will have a prescribed installation procedure such that they are able to perform their roles invariably exceeding the quality levels specified in the repository design. The quality of these barriers will depend on how well they are installed and this depends in turn on proper procedure development, combined with continuous QA/QC activities (testing, verification, sampling, etc.). If sections are poorly placed or damaged by other operations activities, this could provide a localized pathway for radionuclides to move in the borehole, and if such sections are identified, with the technology we propose, it is straightforward (but not simple or quick) to extract the materials and replace them with quality seals. We repeat that the use of a coiled tubing O&G technology with jetting can remove all materials that are not strongly cemented, and that polymeric mechanical bridge plugs can be "drilled out" with coiled-tubing drilling (a mature technology), allowing a higher level of retrievability for a DBP repository than for a mine repository. Figure 6-5 shows a smaller diameter bridge plugs made from cast iron that have to be drilled out with a special bit. The technology for ±600 mm bridge plugs that are made entirely from polymeric materials and can be easily drilled out using coiled tubing drilling methods is considered a straightforward technical development, although not "off the shelf".


*Figure 6-5:* Bridge plugs to seal casings or boreholes (Courtesy: Evolution Completions)

The buffer material will be placed in intervals throughout the entirety of the borehole's canister placement and isolation section and will be placed incrementally as waste canisters are placed. This can lead to sections of the borehole having poorer quality barriers than others. In a similar vein, multiple sealant sections and intermediate mechanical bridge plugs or frictional material intervals can be placed throughout the canister repository section resulting in the possibility of multiple intermediate plugs of sub-standard quality. In fact, with care, it is more likely that there will be very few substandard sections, and that the other, high-quality sections, combined with the master seal and the upper backfilled borehole provide the multiple barriers that reduce pathway development probabilities to exceedingly low values.

Different scenarios will be considered based on the possible quantity and position of defective repository section barriers. Nevertheless, given the robustness of the DBP repository concept and its inherent modular nature, we believe that the escape risk will be as low as or substantially lower than for a mine repository (the most likely standard of comparison, as that scenario has been extensively studied in many places in the world). Remember again that risk quantification entails consequences: if one DBP borehole module is impaired, it is one of many: if a mine is impaired, that mine is singular, and its impairment impacts the security of the totality of canisters.

*Defective Upper Sealing and Backfill System Components*: The upper sealing and backfill system extends from the top of the repository section, above the master seal, to the top of the borehole. The upper sealing section is likely to be separated from the repository section by a carefully emplaced master seal (design to be formulated). Above the master seal will exist various combinations of plugging, sealing and backfill all the way to the ground surface. This will aid in preventing the flow of radionuclides to the near surface environment if the flow is concentrated in the borehole zone. Similar to the barrier system in the repository section, poor placement or sub-standard materials can result in sections of the upper sealing system that are not up to design specifications.

Also like the repository barrier system, the length of the upper sealing system can cause spatial variation in the quality of the system. It is possible to have multiple sub-standard regions through the system resulting in higher permeability zones that allow for more rapid flow of groundwater systems, but these can be compensated for statistically by the presence of many more zones of high integrity. Scenarios will have to be considered based on the quantity and position of defective upper sealing systems.

### 6.4.3 Disturbed repository risk

Disturbed repository scenarios involve situations where the natural barrier system (host rock, groundwater system, overburden) or the engineered barrier system are significantly impacted by events after the closure of the deep borehole. These events result in either a significant change in the mechanism of radionuclide flow, significant change to the assumed site conditions, or significant change to the physical and mechanical properties of the barrier systems. The following disturbed repository scenarios are briefly discussed:

- Human intrusion
- Seismic events
- Volcanism and magmatic events
- Climate change and glaciation
- Erosion

*Human Intrusion*: Human intrusion can be the act of intentionally or unintentionally advancing a man operated drill, probe, or machine into a section of the repository or into a nearby section of host rock. Intrusion can result in a novel high permeability flow path that will allow for rapid flow of radionuclides from the repository to the near surface environment. This possesses both a short-term health risk to the operators of the machinery and a long-term risk to the near surface environment and individuals living in the vicinity of the repository.

Repository studies widely address risks of deliberate or accidental intrusion. Reduction of risk to deliberate intrusion means creating ever stronger barriers that also impair retrievability. Some balance must be struck, and regulators should be aware that, in the limit, anyone can drill a borehole in any rock mass to intersect deeply buried canisters. This means that factors beyond the remit of his report must be examined.

For accidental intrusion risk reduction, previous repository studies have also suggested various means of making sure that human memory is not lost, that the presence of waste is made known to some future high technology civilization capable of penetrating the systems, and so on. The only comment we make here is that part of the site qualification criteria, the absence of mineral values, is important. If there are no mineral values, accidental intrusion is unlikely. In any future society with technology advanced enough to drill through hundreds of meters of granite, there will also exist technologies for mineral detection.

*Seismic Events*: Earthquakes and other seismic events can result in movement and damage to both the engineered and natural barrier system. Seismic activity can result in the generation of a new fault (laterally displaced fractures in rock masses) or the reactivation of existing fault systems. The development or reactivation of faults in the vicinity or that intersect the repository will result in a novel pathway for radionuclides to flow to the near surface environment. Additionally, any engineered barrier system that becomes damaged or displaced during a seismic event will have its ability to inhibit radionuclide flow impaired. We make the following comments:

- Unequivocal seismic quiescence is a site qualification criterion, and the sites onshore in Norway are seismically quiescent and realistically cannot be tectonically reactivated during the life period of a repository.
- Seismic damage is largely a surface wave effect from more remote seismic activity. Subsurface structures such as mines, tunnels, and of course fully confined repository boreholes, are largely immune from significant damage unless directly intersected by a fault.
- Fault reactivation through any repository related issues (pore pressure build up, large-scale stress changes) will not occur because of conservative thermohydromechanical design and the absence of any significant increase in pore pressure and imposed load on the site during construction and operation.

*Volcanism and Magmatic Events*: The development of a large magma chamber below the repository either developing into a volcano or resulting in the development of intrusive igneous structures (e.g., dykes) provides an unusual and highly improbable mechanism for the movement of radionuclides from the repository to the near surface environment. The occurrence of a volcanic event at or near the repository site significantly changes the pathways, fluids, and mechanisms of radionuclide flow considered in the undisturbed analysis. In less severe magmatic events, such as dykes developing in the vicinity of, or intersecting the repository, new high permeability fractures could be developed or fluids with high concentrations of radionuclides could be transported in the magma.

Geological study informs us that we can dismiss this as a possibility in the lifespan of a repository that sits onshore in Norway (i.e., until that time where dose probabilities become vanishingly small).

*Climate Change and Glaciation*: Climate change at the repository site can result in significant changes to the regional groundwater system. These changes can involve the significant increase or decrease of the depth of the water table or the flux of shallow water depending on the climatic conditions. In the extreme scenario of significant global cooling, the presence of glaciers at the repository site is possible. The presence of glaciers could result in 100s of meters of hydraulic head difference compared to present day values.

Whereas these issues lie in the time-realm of possibilities, we are not qualified to evaluate their impacts on the conditions in the repository. We note that in a very stiff, strong rock such as granite or a highly indurated sedimentary sequence, given the depth of burial, glacial erosion is not a tenable risk at any level of probability, and the only real risk, albeit vanishingly small, is a massive hydrogeological regime change that leads to upwelling of water in the repository environment. It has been shown at the Deep Geological Repository site in the Bruce Power site in Ontario, as well as for deep saline solutions in naturally fractured rock masses deep in the Canadian Shield, that appreciable flow has not occurred for millions of years, despite four periods of glaciation in the Pleistocene Era. These studies confirm that even extensive glaciation does not have a significant influence of fluid flow in tight, strong and stiff rock masses. A number of rock mechanics arguments can be brought to bear on the stress-strain history of such rocks to show that it is unlikely that glaciation would significantly impact the possibility of radionuclide escape. However, glaciation would massively reduce the level of consequences of escape (i.e., human dosage levels), so we believe there are no enhanced risks arising from glaciation.

*Erosion*: Erosion involves the removal the top layers of overburden resulting in exposing a buried portion of the earth. This results in the repository "moving up" in the earth as it becomes closer to the new ground surface. Erosion can be associated with major erosional events (e.g., glaciation) or gradual surface processes (e.g., fluvial, alluvial or aeolian processes). Over millions of years, major and gradual erosional events can result in removal of overburden, but the time frame is so long as to make the consequences, and hence the risk, vanishingly small.

We note that in a very stiff, strong rock such as granite or a highly indurated sedimentary sequence, given the depth of burial, given the appropriate choice of site, and given the nature of the erosive processes that can be brought to bear, including glacial erosion, the breaching of the canister interval, or even the removing of 20-30% of the overlying rock, is not a tenable risk at any level of probability.

### 6.4.4 Additional Risk Assessments for DBP

There are other risks associated with the process of placement and isolation of nuclear waste in boreholes that are not within the scope of this report, which is limited to DBP repository issues, focusing on rock behavior. In future analyses, risk associated with the following factors will have to be considered when evaluating the selection of a repository site and overall design of the repository:

- Transportation
- Temporary on-site storage
- Security
- Waste canister design and encapsulation process

## 6.5 Summary

We have shown that risks can be identified and mitigation methods can be implemented at all stages of DBP repository qualification and operation. In fact, we believe that the DBP repository concept benefits from several inherently safer characteristics, in comparison to the mine repository concept.

- The DBP system is inherently modular. Thus, impairment of one module does not impair other aspects of the repository development.
- Operations are taking place at surface, not underground, giving direct line-of-sight control, full-field access, and climatic dispersion and dilution mechanisms (wind, rain) that would serve to mitigate consequences if an accident happens.
- At all stages of the process of creating a suitable placement borehole, there are qualification steps and procedures that allow risk reduction in an adaptive management framework.
- The boreholes, given their small cross-sectional area, are inherently amenable to extensive conservatism in terms of the design of multiple seals, buffer materials, mechanical bridge plugs and backfill.

Nevertheless, because waste canisters and seal/buffer materials must be placed remotely downhole, careful QA/QC must be exercised throughout the placement and sealing process. We believe that existing O&G industry and mining industry technology, suitably deployed, can reduce the risks of radionuclide escape during and after sealing to acceptably low values. The DBP repository approach appears to be a technically workable concept at all stages, leading to a high level of waste security for a long period of time until the toxicity of the wastes has decayed to a level where a dangerous dose to a human is highly improbable.

# Chapter 7: Repository Design and Rationale

## 7.1 Introduction to the Repository Design

The concept of Deep Borehole Placement (DBP) for radioactive waste is not new (O'Brien *et al*., 1979; Brunskill, 2006); it has been proposed in various modes for different waste types in different geological environments for several decades (e.g., Pusch *et al*., 2012; Arnold *et al*., 2011; Brady *et al*., 2009; Nirex, 2004). Suggestions vary from holes many kilometers deep (5-6) to shallower configurations, including multilaterals, horizontal wells, highly deviated wells, and so on. An example of a proposed deep borehole isolation concept is shown in Figure 7-1.

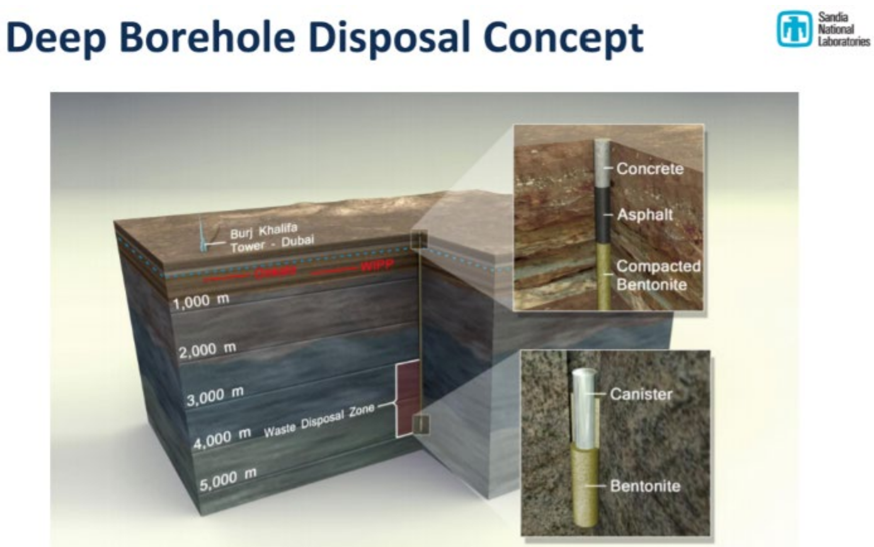


*Figure 7-1: Deep Borehole Placement (DBP) concept – Sandia National Laboratories (Courtesy: public slide presentation by Bill Arnold and Pat Brady, Rapid City SD, USA, 2013)*

The deep borehole placement concept in the past is generally developed in the context of oilfield technology and sometimes the placement site is perceived to be deep in sedimentary basins, although deep crystalline rocks are more often the target placement sites. We will contrast some issues with those that may arise in a mine placement concept shown in Figure 7-2.

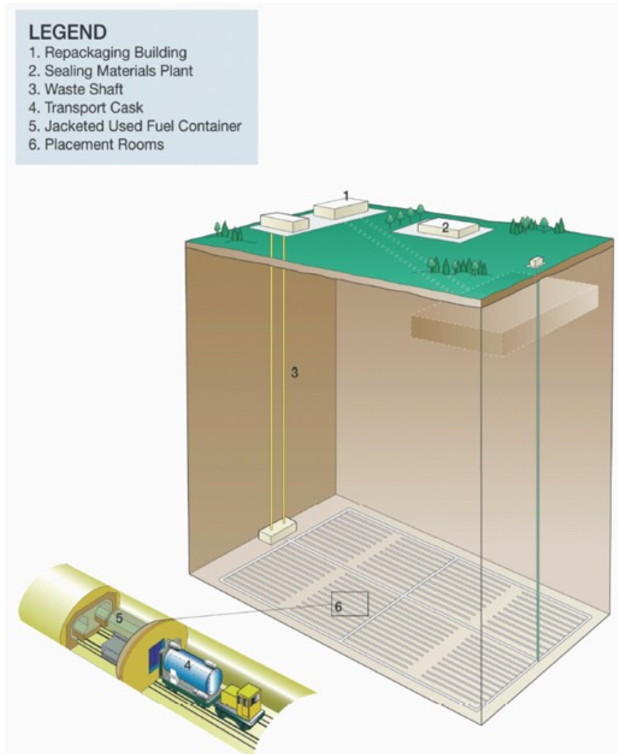


*Figure 7-2: Mine placement concept (Courtesy : NWMO)*

Although the extensive work of the NWMO in Canada has helped inform us and is truly exhaustive in most aspects of science and technology, particularly the studies related to the potential mine repository at the Bruce Nuclear site (DGR – Deep Geological Repository), our focus is on borehole placement exclusively. Furthermore, we focus exclusively on deep borehole placement in crystalline rocks (granites, gneisses, basalts), some low porosity metamorphic rocks (greenstones), or highly indurated sedimentary rocks (low permeability, low porosity). For discussion purposes, and considering Norway's geology, we generally assume as a default scenario that the borehole placement section for waste canisters is in a competent granitic rock mass. We also note that this restriction on host rock choice means that fluid flow systems will be in natural fractures, not through the rock matrix, and that all sealing aspects for the rock mass must focus on the existence of natural fractures (joints) as potential pathways.

*The Retrievability Issue*: A major concern in the past has been that the requirement for "retrievability" of high-level wastes (HLW), a principle of nuclear waste repository design, cannot be met by a Deep Borehole Placement (DBP) approach (e.g., Winterle *et al*., 2011). Pusch *et al*. (2012) say: "*Retrieval of damaged casings and stuck canisters may be more difficult than in mined repositories.*" This concern is worth discussing. First, contrast large-diameter (600 mm) DBP post-closure with a mined repository that has also been fully "closed". The issue of retrievability appears equally complex in both cases: re-entering a closed and sealed mine, removing the backfill, and safely locating and recovering canisters that may not have retained integrity seems no less challenging than re-entering a borehole, reaming or jetting the backfill and buffer material to the level of the canisters, and recovering the canisters.

Thus, considering the retrievability issue, it is our opinion that it should not be a negative issue in the DBP repository concept evaluation because such an approach appears to lead to an emplacement condition no less retrievable than a closed, backfilled mine. Also, design elements can be implemented in the barriers and sealants to improve drilling control and retrievability during some future recovery efforts. For example, canisters will not be "cemented into place", and above each canister a layer of natural asphalt can be placed as a seal, such that the recovery activity has a clear marker related to the vertical proximity of the canister. A claim that deep borehole placement leads to irretrievability appears not justified for the DBP scenarios we analyze. We believe that a DBP repository can be designed and waste emplaced in a manner that retrievability, using oil and gas industry and mining industry technology, is feasible and as safe as for a deep mine.

*The Evolution of Repository Concepts*: Repository concepts and drilling technologies continue to evolve, and even the conditions and constraints considered a decade ago may be different at this time, and will change in the future. Before proceeding to repository site choice and qualification studies, a full-scale, 1-km deep example project (the DBP Test Facility – Appendix I) will be necessary to demonstrate proof-of-concept. As part of such a preliminary demonstration project, the issue of a retrieval process will be studied in detail and could even be developed and demonstrated in practice.

Consider some of the other concerns voiced in Pusch *et al*. (2012). In their analysis, they posit that "… *precise adaption of canister and seal positions to the rock structure cannot be made until boring of the deep holes is complete*." This comment seems not fully justified, and we do not believe that this is a constraint for DBP in highly competent crystalline or low porosity indurated sedimentary rocks. Again, in comparison to canister placement in holes drilled into the floor of a mined repository room, there is no reason to believe that precise wireline placement of surface canisters at depth, followed by backfilling with a buffer material and seal intervals, would result in any lower quality outcome, especially in comparison with quasi-robotic (remote control) underground mine placement. It appears that placement from the surface using wireline hoisting methods and coiled tubing technology gives far greater flexibility in terms of the possible activities and means of coping with situations. For example, a serious machine accident underground blocking a roadway is extremely disruptive; on the surface, far less so. There are many advantages and lower operational risks to having the placement and sealing procedure take place from a surface site.

Pusch *et al*. (2012) suggest that "…*the deep holes need to be supported by casings and all work deeper than 500 m must be made with mud in them*." This is not relevant for the scenario presented in this report. Holes can be advanced to considerable depths (several kilometers) without the need for casings if the rock mass is highly competent (granites), and the use of drilling mud may even be avoided because there is no requirement for control of high pressure fluids at depth in a rock mass that is functionally impermeable. Because of the great geochemical stability and competence of dense, low-porosity sedimentary or low-grade metamorphic rocks such as phyllites and siltstones, and igneous rocks of a granitic nature, it does not make sense to use a steel-cased and cemented hole for HLW placement. These substances (steel, cement) are not geochemically stable; it appears better to rely on the undisputed stability of the minerals in the host rock and not introduce materials that can decay and degenerate, potentially leading to pathways at some distant future. The natural minerals in the rock mass do not degrade (swelling, chemical changes) in the presence of drilling fluids, therefore exotic drilling fluid compositions are not required to sustain borehole stability (as in the case of shales and soluble minerals such as halite). There are no chemical reactions between drilling fluids and the normal suite of minerals found in extremely dense clastic sedimentary and crystalline rocks.

To address a technical construct such as a DBP repository concept, it is useful to address a particular scenario. We focus on the high-level waste placement aspect, the issue of greatest environmental concern, and assume that the placement of intermediate- and low-level waste capsules will be far more straightforward. The specific details of a final DBP repository design depend on a large number of studies related to:

- The nature of the waste (e.g., its energy output over time as radionuclides decay)
- Waste volumes to be placed at depth in canisters (amount of waste per canister and number of canisters), including information about the concentrations of radionuclides so that thermal calculations are possible
- Canister design, including diameter, length and attachment systems for hoisting and lowering the canisters during placement and potentially during some future recovery activity
- Specifically chosen performance issues and risk levels imposed upon the repository design by the regulatory authority or the technical committee, such as maximum rock mass temperature
- Assessment of the deep saline groundwater flow system and the geochemical signatures to determine flow rates, age of groundwater, and other factors

Because many issues remain to be decided, a reasonable case must be delineated based on a set of assumptions. We have chosen a siting scenario assuming the following main characteristics:

- A location with little or thin surficial deposits, therefore there is no local potable water system to perturb, as might be the case with a significant sedimentary cover;
- A site that is reasonably flat or can be made flat readily so that an array of boreholes can be developed in a realistic manner, with the possibility of partial robotic/remote control

actions during the canister emplacement and sub-surface sealing phase activity of each placement borehole;

- A subsurface geology comprising dense, competent crystalline rocks (or low-porosity sedimentary rocks) with:
  - Impermeable or extremely low matrix permeability characteristics;
  - Little to low levels of natural fracturing, and an absence of severely fractured zones;
  - Static and stable deep flow regime, with fluids density graded for convective stability;
  - Absence of significant permeable horizons such as a permeable fracture zone or fault gouge zone, a fractured paleosol, or karstic features of any kind;
  - Normal or low (geothermal) natural temperature gradient;
  - Absence of any potential for vulcanism or rekindling of tectonic forces for the indefinite future (stable cratonic conditions);
  - Normal pore pressure distribution with depth (no overpressure), as is characteristic of groundwater recharge regions;
  - Absence of soluble or reactive minerals, ores and fossil fuels; and,
  - Absence of any deeply weathered horizons where there may be concern as to the development of pathways in the long term.

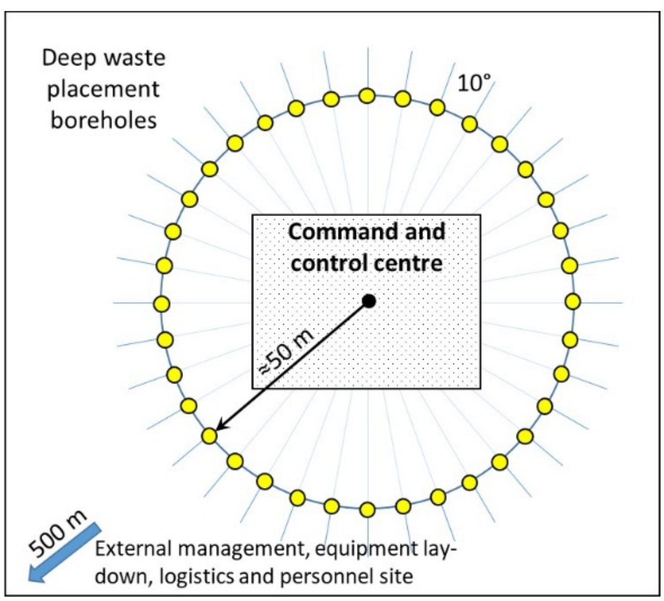


*Figure 7-3: DBP repository surface layout*

The surface layout of a DBP repository is suggested in Figure 7-3. The rationale and discussion of such a layout is addressed in following sections. The depth we have chosen to analyze is a one-kilometer-deep, large-diameter borehole array. This choice is entirely for purposes of analysis and delineation of technology options; in an actual final design, the depth may be chosen to be greater than this value, or other alterations made, depending on the perceived and calculated risk factors, and the design of the canisters and capsules.

The array depicted is circular in nature. This is an arbitrary choice, and the final disposition of the boreholes will depend on site properties, access, and geological factors. The 36 equally spaced boreholes shown is also an arbitrary choice; design factors such as volumes and number of canisters will lead to different decisions. For example, the design may involve placement of low-level or intermediate-level wastes into two out of three boreholes, limiting the number of boreholes with high-level waste canisters. Many options are feasible.

An advantage of a DBP repository is that the disposition of the wastes is a modular activity; the need for more or fewer boreholes is dictated by their use and by the volumes of waste to be placed. Because of this modularity, the actual borehole development and waste placement activities will scale approximately linearly, once the basic site is prepared. This is not the case for a mine, where the up-front costs for a mine dominate all economic and risk analyses. The next diagram shows a cross-sectional view through the middle of the scenario DBP repository with the distances being a function of the size of the surface array and the 10° outward dip of the boreholes (Figure 7-4).

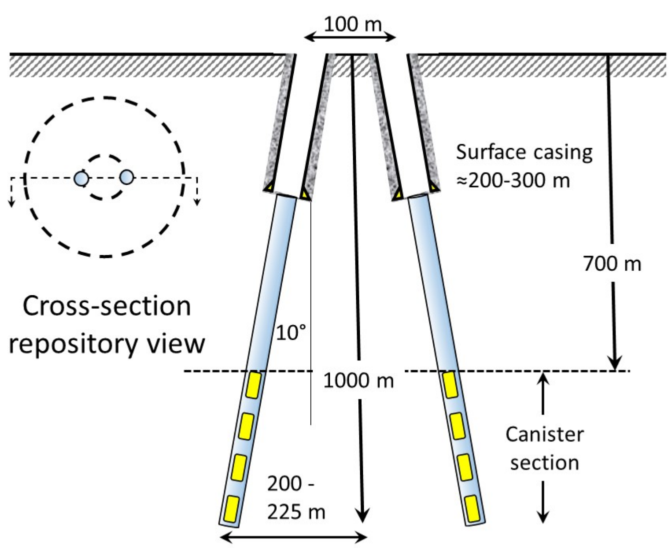


*Figure 7-4: DBP repository cross-sectional view*

Lithologically, providing the characteristics above are met, the geology of the site may comprise any of these three scenarios:

- A continuous column of competent crystalline rocks in a stable craton;

- A continuous column of competent sedimentary rocks lying on a stable craton; or,
- A sedimentary sequence lying above a crystalline basement cratonic sequence.

For illustration, providing all conditions are favorable, the geological disposition shown in Figure 7-5 is acceptable as a repository site.

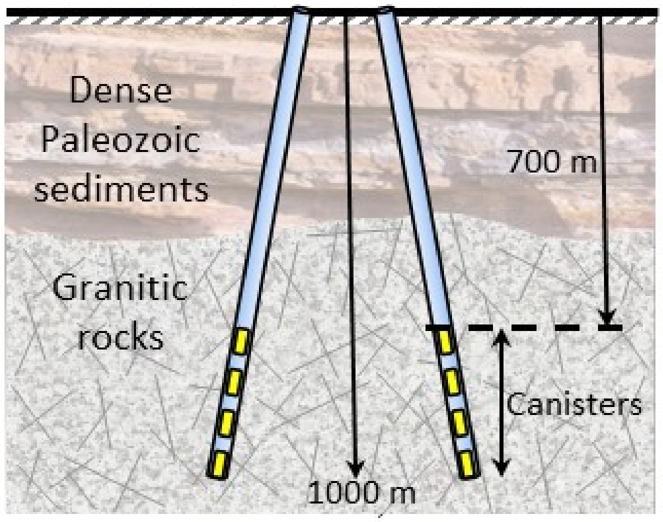


*Figure 7-5: Low permeability Paleozoic strata overlying competent crystalline rocks*

## 7.2 Array Design, Safety and Access

This report deals primarily with the geomechanics aspects of the feasibility of deep boreholes in competent rock for radioactive waste placement. Other security and technical dimensions may affect rock mechanics and drilling issues; many of these have already been discussed, and wherever possible, issues are pointed out.

### 7.2.1 Surface Design Issues

The working site shown above is a compact layout with a central command and control structure and easy access to all borehole locations. The materials storage and equipment lay-down yards are located outside of the array at a sufficient distance, such as 500 m. Only actively working personnel and supervisory staff would be allowed within a perimeter containing the array. During the waste transportation and placement period, site personnel control and safety protocols will be much more rigorous than during the drilling program.

The surface layout of the deep borehole array is limited in area for the following reasons:

- A smaller area site is easier to prepare and use, and has a smaller environmental and land-use footprint, in general. Economically, this gives advantages, and in terms of safety, shorter distances likely mean lower risks of accidents of all types, and a shorter path to a safe area in general.

- Transportation and equipment moving costs are lower, and the site can be readily electrified. If a drilling rig or coiled tubing unit that has to be skidded is chosen, the surface locations are close enough that skidding between locations is straightforward.

Visual contact and control are important aspects. Movement of personnel and equipment can be more easily seen and controlled if a full line-of-sight is maintained between a central office building and the array of possible work places. Line of sight management can survive unexpected events such as a general power outage.

### 7.2.2 Subsurface Design Rationale

The guiding principles chosen for the subsurface design are based on issues discussed in the literature related to thermal effects, long-term pathway development, and comparison with alternative approaches, in particular, contrasting a deep borehole concept compared to a hypothetical mine repository.

- Widely spaced canisters in a large rock volume are preferred, in part to minimize thermal effects, in part to provide barrier redundancy, in part to lengthen potential pathways that might exist or develop.
- The presence of more saline water at depth favors deeper placement: in principle, DBP approaches can provide deeper access than mine scenarios, which are usually less than a kilometer deep.
- Avoidance of steel, cement, or other man-made materials that lack indefinite geochemical stability is a goal of the design; this is more easily achieved in a DBP scenario.
- Related to the previous principle, the geochemical stability of a natural rock material and its compatibility with existing groundwater are advantages that should be used as much as possible.
- There is a high stability level and low level of rock damage in a competent dense rock drilled with current technologies.
- Implementation of a guide hole approach for the development of each large diameter waste placement hole allows detailed assessment of each case (full re-qualification) to identify potential anomalies, and it also serves as a means of guaranteeing precise trajectory control.

Figure 7-6 shows a conceptual borehole design approach. The bottom zone contains canisters, with buffer and sealants. The upper part of the borehole is backfilled with dense granular backfill (drill cuttings), perhaps lightly cemented with a geochemically stable material, and perhaps some intermediate sealed zones if there are natural fractures that have any flow capacity.

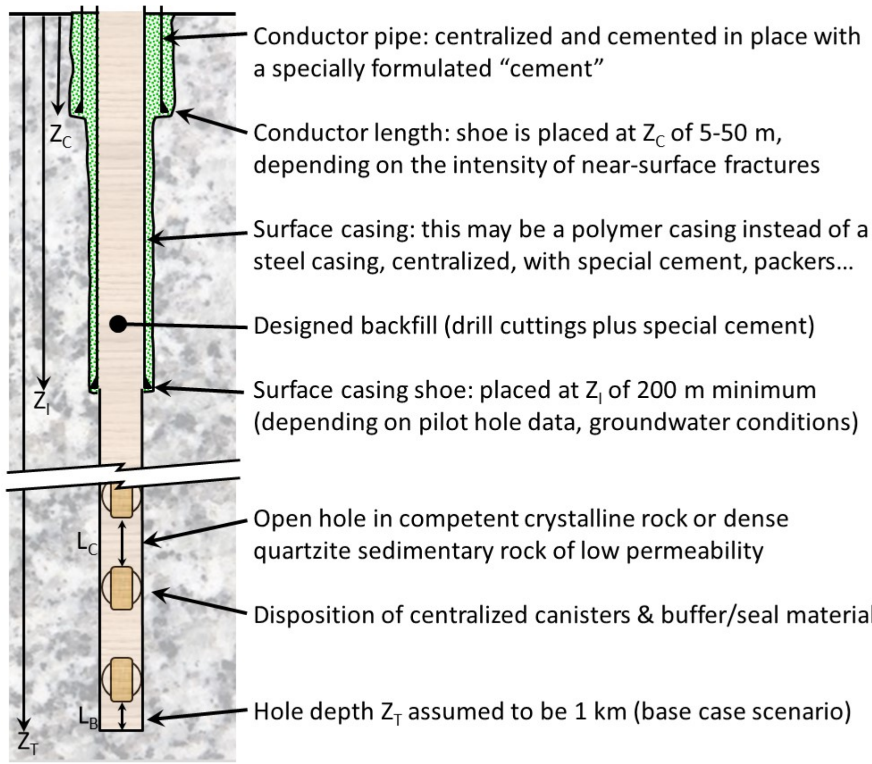


*Figure 7-6: A conceptual diagram of a placement borehole for waste canisters.*

*Canister Spacing*: Large spacing distances between canisters is straightforward in a DBP repository, compared to a mine repository, because of the three-dimensional placement of the canisters. Both lateral and vertical distancing can be adjusted to meet relevant regulatory and design criteria. The depth and inclination of the borehole array, as well as the number of boreholes, can be altered during the qualification processes, the final design phase, and even the repository development phase. For example, a repository could be limited to 10 or 20 boreholes (each rotated 36° or 18° rotated from the adjacent hole in a circular array). The boreholes can be deeper – 1.5 to 2 km or more instead of 1 km. The inclination angle can be increased slightly, but it is best to remain at 10° because of wireline emplacement effectiveness and ease. Each second borehole around the circular array could be drilled 300 m deeper to encompass more overall rock volume and increasing inter-canister distances.

Because each borehole will be individually sealed and the chosen site will have extremely low connectivity between the canister sections of each borehole due to the wide spacing at the base of the boreholes, the probability of a break and leak contaminating several of the boreholes and canister sections is vanishingly small. This is in contrast to a mine, where the array of canisters in a room is relatively closely spaced, and a fugitive radionuclide event would impair, at the very least, the local array, and perhaps the entire mine. Thus, because of the modular and separated nature of the DBP repository boreholes, they are inherently more resilient to accidents.

The thermal conductivity of granites is well-known (2-6 W/mK), and thermal calculations can be carried out to choose an upper temperature limit, once the energy output over time for the waste canisters is specified, and once borehole heat flux experiments are conducted during the site qualification phase. Given the three-dimensional nature of the array, in contrast to the two-dimensional nature and the close spacings that are typically used in mine repositories, the thermal impact on the rock mass is much easier to manage. The thermal footprint ($\Delta T$) will be much lighter than in a two-dimensional mine repository.

*Convective Stability of Saline Fluids*: With depth, the small amounts of water in an igneous rock mass are found to be more and more saline, usually with NaCl, but also with $CaCl_2$ in many cases (Frape *et al*., 1984). This means that the liquids are density-graded, with less dense fluids closer to the surface of the earth, and more dense fluids at depth. This density gradation is strong in the case of natural brines, which approach a density of 1.2 g/cc for pure NaCl brines, and a density of over 1.3 g/cc for $CaCl_2$ brines. In the Canadian Shield, high-density Na-Ca-Cl brines are ubiquitous at depths below one kilometer, and such conditions are expected in the crystalline cratonic rock masses in Norway. This high density at depth is a strong suppressant of upward flow (Brunskill, 2006), leading to a condition of convective stability, where the deep saline waters are essentially stagnant or extremely slowly moving over millennia. No significant natural upward movement can take place from great depth in these regions, and even if the natural deep brines are heated somewhat, they remain as dense liquids with only a potential for lateral flow, and very limited vertical flow potential. In a DBP repository case, even if canister heat emission raises the temperature of the minute amount of fluids in the deep igneous rock, the density is affected by only a small amount, so vertical flow as the result of heating alone is, realistically, impossible.

For example, Winterle *et al*. (2011) mention thermally stimulated groundwater flow as a pathway mechanism, but in the presence of a strong density increase with depth, it is not energetically possible to overcome the natural barrier to upward flow by thermal convection.

*Stable Materials*: The use of materials that are geochemically unstable in the geosphere over millennia is not advised, and is to be avoided whenever possible for all aspects of the borehole construction. For example, conventional steel goods used as casings corrode with time, undergoing acidic degradation if certain conditions are met (Hutcheon, 1998).

Carter, Fortner, Skuce and Longstaffe, 2014, Aquifer Systems in Southern Ontario: Hydrogeological Considerations for Well Drilling and Plugging, CSPG Calgary

*Figure 7-7: Sulphates or sulphides (e.g., pyrite), and bacterial (archaobacteria) activity may corrode steel (Courtesy: public presentation by T. Carter, Private Consultant, Ontario)*

Hydraulic cements such as Portland cement and many other commercial products that are manufactured by high temperature reactions are unstable geochemically over millennia (Trotignon *et al*., 2007); the corrosion and degradation of cement has the potential to create pathways, and therefore should be avoided. The most common reactions that degrade the cement quality are carbonation reactions in the presence of weak carbonic acid ($H_2CO_3$) and low-pH $SO_4^{-2}$ water (gypsum, anhydrite sourced) that generates acidic components that gradually act upon the geochemically unstable cementitious components. Other more stable seal and backfill materials are available and should be used.

In addition to the issues of steel and cement instability, it is expected that the canister design and materials are chosen to minimize any tendency for gas generation. We also note that gas pressures generated at depth are most likely to lead to lateral flow because of the density of the aqueous brines in the rock mass, but gases do have buoyancy, and this has to be evaluated in the context of the DBP repository and the suppression of any vertical migration potential along the large diameter boreholes through seals, plugs and placement of backfill with small pore throat distributions (well-graded granular backfill).

<u>*Natural Materials*</u>: The most stable materials in the repository environment are the natural minerals, in particular the felsic minerals (quartz, feldspars, muscovite) that characterize granites and many sandstones and siltstones. These materials will not degrade over the time frame of a repository life (hundreds of thousands of years for high level wastes), and their use is to be favored over other materials as much as possible. They will not degrade significantly on exposure to radiation nor will moderate temperatures affect their mechanical and matrix hydrogeological behavior. Furthermore, these minerals are in geochemical equilibrium with the small amounts of water in the rock mass, and are functionally insoluble over the range of conditions that will be

encountered, or that could be expected to develop in the future. Some other natural materials of potential value in barrier creation include sealants such as natural asphalts and gilsonite, which can be made ductile through heat to facilitate sealing. Sealant material such as a molten (heated) mixture of 50% asphalt and 50% fine-grained quartz ($SiO_2$) flour will, for example, be easily placed in a dry hole, and once solidified will exhibit great geochemical stability and retain essentially zero permeability indefinitely.

*Mechanical Stability*: The granite or dense (low-porosity) rock in the borehole wall is expected to be of high strength, with an unconfined compressive strength (UCS) generally of 100 MPa or more. Site qualification will preclude poor rock conditions such as extremely deep weathering, intense fracturing, and disaggregated rock. We assume a rock mass with a strong brittle matrix.

In a borehole wall, a rock of 100 MPa UCS will remain intact without spalling to depths of 1.5-2.0 km, even with lack of support by a fluid (water or drilling mud). With some fluid support, greater depths are easily attained without degradation of the rock in the borehole wall. The drilling process (percussive drilling is assumed) will generate a thin annulus around the borehole wall where some rock matrix damage in the form of crystal boundary microcracks and grain facture can be noted. This annulus is not considered an effective potential pathway because of the narrow aperture, short length, and lack of connectivity of the microcracks. This issue can be more carefully studied, and different drilling approaches taken if required, but we suggest percussive drilling technology for the large diameter boreholes is appropriate.

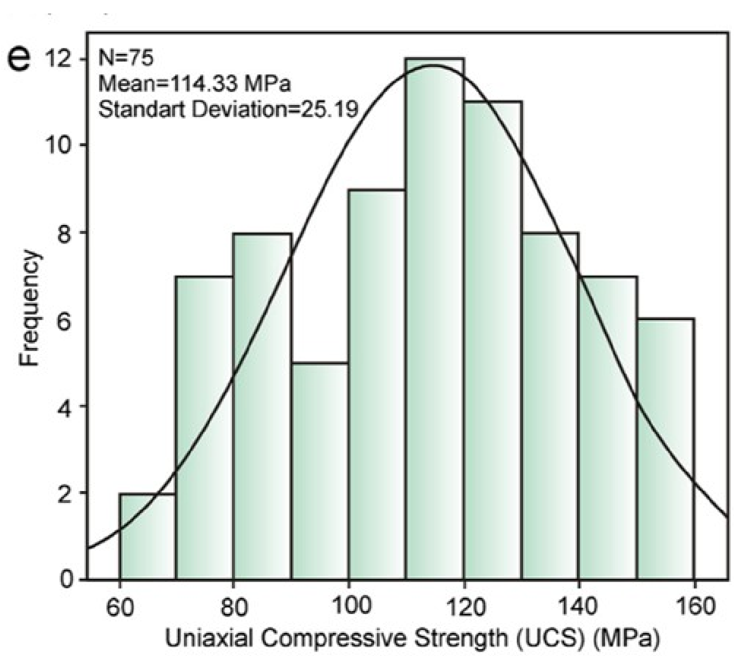


*Figure 7-8: Unconfined Compressive Strength (UCS) of Granites (Yesiloglu-Gultekin et al., 2013)*

*Individual Borehole Qualification*: The process of putting a large diameter borehole into place starts with controlled directional drilling of a small diameter guide hole for accommodating the large diameter drill mandrel. This guide hole can be drilled with a small diameter air or water hammer percussive process. If desired, any single guide hole or all of them can be continuously diamond cored through the canister placement zone, or through any zone that is deemed of interest. Whether or not the guide hole is hammer drilled or continuously cored, a full suite of geophysical logs is acquired, including televiewer logs, and carefully studied for the presence of any anomalies. Borehole flow tests and other evaluation measures can also be taken at this stage before the expansion of the hole to ≈600-800 mm diameter. Extensive testing can be carried out with a coiled tubing unit, specially equipped for this application. This individual borehole qualification procedure provides an opportunity for direct decision-making for each placement hole individually, and the data are also added to the GEM for continued detailing of the site geo-model. If the guide hole inspection indicates an anomaly that is of sufficient concern to the advisory experts, the hole can be sealed and abandoned, used only for low level waste capsules, considered for amelioration through special sealing techniques, converted to a monitor borehole, or a decision to go ahead may made on the advice of the expert evaluations provided.

As a relevant operational example, lowering canisters or capsules down a 10° inclined hole may raise issues of canister hang up, undue abrasion, and so on. We note that drill holes advanced with a guide hole and mandrel are generally smooth and straight, serious flaws (pervasive close-spaced jointing) likely disqualify holes or may be rectified (installation of a patch), and all holes will be completely surveyed before placement. This assures that no impediment to canister lowering exists before placement, and re-surveying of the hole can take place at any time during the placement process. A 10° inclination was deliberately chosen for several reasons: it provides good distancing between boreholes at depth; it is steep enough to allow lowering without excessive friction against the hole walls; and at 10° the weight of the canister and harness is sufficient to keep the lowering process stable. Canister and capsules can be designed with suitable rounded corners id there is concern, and plastic centralizers can be attached and deployed before lowering so that the canister remains in the centre of the bole, not touching the borehole walls during lowering.

### 7.2.3 Naturally Existing Barriers to Fluid Migration

There is wide agreement that any serious breach of containment for a repository will necessarily involve fluid flow. What natural barriers exist to fluid flow in a deep granite rock mass or a highly indurated and low-porosity sedimentary rock mass that is host to a DBP repository?


*Figure 7-9: Heavily weathered granite with joints, Tasmania, Australia*

*Figure 7-10: Flat-lying, weathered and jointed sedimentary strata*

Figures 7-9 and 7-10, in an exaggerated way because of the intense weathering, exemplify the geological engineering view of a naturally fractured rock mass. The rock mass comprises two contiguous systems:

- the rock matrix, which at depth accounts for over 99.9% of the volume, and,

- a system of natural fractures referred to as joints, which accounts for less than 0.1% of the system volume (in the absence of karstic features, vugs, or other macroporous elements).

*Inherent Low Matrix Permeability*: Intact (unweathered) granites have matrix porosities that are less than 1%, and this porosity is not in the form of an interconnected flow network. Similarly, dense shales and the low-grade metamorphic products of shale (slates and phyllites) may be considered to have impermeable matrices. Extremely dense shales, clayey siltstones and fine-grained lithic sandstones with porosities less than 2-3%, as well as their low-grade metamorphic products, pelites, have permeabilities in the nanoDarcy range. Dolomites and limestones of very low porosity have similarly low permeabilities. Hydrated cations (e.g. radioactive metallic atoms) cannot flow or diffuse significant distances through intact granite matrix or other dense rock matrix in any repository time frame. As quartzose sediments densify through diagenetic processes at depth, silica minerals are dissolved and precipitated, partially or completely filling pores and greatly restricting pore throat sizes. As an example of low permeability Paleozoic sediments considered suitable for a mine repository site, the Ordovician and Silurian strata approximately 550-700 m deep in the Goderich area of Ontario are low-porosity, very low permeability quartzitic sediments that have not been tectonically deformed. Site qualification for the DBP repository will verify that the permeability of the rock matrix is in the nano-Darcy range, a natural barrier against matrix flow.

*Condition of Deep Natural Fractures*: Intrusive igneous rocks (e.g., granites, diorites, deep basaltic laccoliths) undergo cooling after magmatic formation and the associated locked-in stresses arising from solidification at great depth lead to the formation of tension cracks as these competent rocks are gradually brought toward the surface and experience stress relief through erosion (Price, 1959; Mandl, 2005). These cracks are called joints, and the spacing between the joints is a function of many variables (grain fabric, tectonic influences…). However, in a granite pluton that has not experienced subsequent tectonic deformation or hydrothermal processes, the joints are far apart even at surface (several meters in some cases), but at depth tend to be far less frequent, tightly closed, and often re-cemented with precipitated quartz (Sousa, 2007). In crystalline rocks, another form of joints close to the surface, “sheeting joints”, will exist. These are joints that are roughly parallel to the exposed surface of the rock and caused by stress effects, helped by thermal strains and weathering processes. Sheeting joints are generally not found at depths below 100-200 m in intact unweathered plutonic rocks that have not been subjected to tectonic restressing.

Some igneous rocks that are emplaced at shallow depths experience thermal shrinkage, causing the formation of natural fractures. Sedimentary rocks undergo shrinkage through several diagenetic mechanisms as they become more and more lithified and indurated, and this leads to the formation of joints, usually in a quasi-regular pattern, as shown in the lower photo above. In dense and diagenetically altered sedimentary rock, it is common that the joints have been re-cemented through the deposition of calcite or quartz.

Part of the site qualification process and continuing QA/QC activity will be to test and thereby quantify the conductivity of joints that are identified in cored sections, or in geophysical log data, and in guide holes, to insure that the conductivities are low. Part of the decision-making process is to choose the conductor casing shoe depth and the surface casing shoe depth to isolate the shallower naturally fractured features and sheeting joints to reduce the potential for migration.

*Convective Stability of Saline Fluids*: As mentioned above, the water at a repository site will become more saline with depth, giving a natural barrier against upward convective flow.

We conclude that in a qualified repository, it will be determined that any significant fluid flux from depth toward the surface will be exceedingly unlikely. Furthermore, there are additional natural barriers that exist and that will be better quantified during site qualification, including these aspects:

- Natural retardation of migration of dissolved ions through surface sorption on minerals
- Low solubility of the molecules in which radionuclides are found (these molecules are never soluble chloride or bromine salts; they are other low-solubility mineral forms)
- Long flow path because of great depth and dominantly horizontal flow in a density stratified pore water environment

## 7.3 Sequence of Events

The basic sequence of events to occur with respect to the qualified site in order to create a repository using deep boreholes in a high quality rock mass is complex and will be delineated by the DBP technical committee in consultation with available scientific and construction expertise. Some highlights are noted here for discussion.

*Pre-Design Data Acquisition*: It will be necessary to have a clear picture of the goals of the repository in terms of capacity. This will require at least the following data to be decided in the pre-design (pre-FEED) phase:

- Proposed final canister design, geometry, protective sheath (harness), materials for sheath, centralizers, handling hooks, etc.
- Number of canisters
- Volumes of intermediate- and low-level wastes to be co-emplaced in the repository (i.e., along with but not necessarily in the same boreholes as the high-level wastes) and their encapsulation design
- Final chosen depth and diameters for the large-diameter emplacement boreholes
- Final choice of numbers of boreholes, e.g., with a 20% safety margin

- Minimum regulated vertical spacing between canisters
- Minimum lateral distances between canister sections at the bottom of the boreholes
- Set-off distance from any geological feature at the site that may be deemed an anomaly of interest (e.g., a small fault, a more intensely fractured region…)
- Specific guidelines for buffer material placement stipulated by the regulator and technical committee
- Plans for intermediate-term and long-term monitoring implementation, especially any monitoring that will be placed in independent boreholes or in the waste boreholes during the sealing process
- The number of guide holes that will be cored, fully or partially, including the suite of geophysical logs required in each guide hole, the rules for flow testing or mechanical qualification of guide holes and emplacement holes should anomalies be detected, etc.
- Choice of conductor pipe shoe depth and choice of surface casing shoe depth, based on data from the site qualification activity
- Choice of materials to be used in boreholes, most importantly, the nature of the casing material and the cementing material to emplace the casings securely and indefinitely
- …and other information that will allow the actual design phase to take place.

*DBP Test Facility*: We advise that a pre-FEED set of full-scale experiments be carried out at a DBP Test Facility that will become a training facility after FEED. A brief proposal has been filed (Appendix I).

*FEED – Front-End Engineering and Design*: FEED activity realistically starts when a contract is awarded to an appropriate engineering company that will create a suitable design for the project. Because of the nature of the project, a high-level waste repository, the design will not be rigid, as evaluation points and decisions to be made will be encountered throughout the construction phase, maintaining QC/QA at all times to meet the regulatory and technical goals. There will also be stipulated areas of expertise that must be included in the FEED process, and it is not likely that all of the necessary expertise will be found in one corporation. For example, if an integrated corporation such as SINTEF A.S. is chosen to do the design (one of a handful of potential candidates), they may have to seek a sub-contractor in the mining drilling area to help the FEED process.

The FEED document will clearly outline the technical details, the timing of the project phases, the number and types of subcontractors needed, the management structure for the project, and all major related organizational and technical needs. FEED leads to a document or documents that can be circulated for bids in certain domains, or certain suppliers may be stipulated, depending on the technical and regulatory activities that have preceded the FEED activity. For example, if a company has participated in developing and testing a casing cementing material for the agency, stipulating their involvement as a sole-source supplier is legitimate. Because of the unusual (non-conventional) nature of the project, lowest-cost service providers will not be necessarily chosen; stipulated providers or “best of class” providers may be chosen.

*Site Preparation Phase*: The site is cleared, access developed, power is brought in (depending on location), the surface is modified to allow the design to be executed (e.g., some blasting and laying of cement surfaces and roadways will be required), buildings are placed appropriately, serviced, and environmental aspects put into place (water, sanitary services, waste collection and treatment…). A command and control structure with some technical services (repair shops, compressed air provision, maintenance equipment…) in the centre of the surface repository location is advised. It is likely that canisters and capsules are brought to an adjacent mobilization site, but the detailed handling of canisters and other wastes will be limited to the central repository site during placement, and provision must be made for this careful material handling process. It is not recommended that canisters be stored on the operations site for any appreciable length of time: wastes and canisters can be logistically managed from a more distant source to coordinate with site activity and to provide for safe transport conditions. One canister at a time on the surface at the site is recommended.

The general facilities area (equipment storage and maintenance, materials warehousing, mobilizing locations for assembly of components, change rooms, cafeteria, rooms if on-site living is needed, first aid centre…) is approximately 500 m distant and suitably located for access and departure on the entry road before the repository site is reached.

Security will be an issue, and the site geography and control must reflect the level of security needed. The site will be equipped to transition from a “low-security” condition during guide hole drilling and site preparation, to a “medium-security” condition during large-diameter borehole drilling, to a “high-security” condition when waste materials and isolation barriers are being emplaced. The entire site (repository site and the larger area including the general facilities area) is fenced and protected, likely with three security areas:

- Entry to the general facilities area through gated security for screening of service providers of all types, delivery vehicles and other needs, combined with electronic access and control for site employees and designated contractor employees (persons operating the warehouse, the cafeteria, all external services and logistics, cleaning and maintenance of the general facilities area, etc.);
- Entry to the secondary fenced medium-to-high security area containing the repository borehole sites and work places will be limited to safety-trained, tagged personnel who are actively involved and have been pre-cleared, with electronic verification; maintenance and cleaning personnel that have also been similarly pre-cleared, and other “essential” workers needed to advance the project; and,

- Dual identification (e.g., biometric verification plus visual identification) controlled entry to the command and control part of the buildings in the centre of the repository site where regulatory representatives, management, supervisory engineers, technicians, and other personnel with stipulated responsibilities are working actively, where data collection is occurring, where communications systems are operating, and so on.

Consideration should be given to a separate roadway for entry of waste material when the placement phase is undertaken.

*Guide Hole Drilling*: It is recommended that the phase of guide hole drilling, combined with the installation of any additional monitoring holes or systems, take place entirely or mostly before the phase of large-diameter borehole drilling takes place. The reason for this is simple: the data collected from the guide holes will allow pre-identification of any geological anomalies, will populate the GEM with the additional information to allow technical decisions to be made, and will be considered to be the information allowing the "final phase of site and individual borehole qualification". It is recommended that the guide hole drilling activity starts soon after the site preparation activity starts (once preliminary access and power are available, for example), and may even be largely completed before all the site preparation activity is completed. This is to develop a clear GEM soon in the process to guide technical decisions and qualification.

*Large Diameter Borehole Drilling*: The equipment is brought in for the large-diameter repository borehole drilling phase. We believe that it is most appropriate that this take place largely before any radioactive waste is emplaced. Depending on the volumes and nature of the wastes to be stored in the boreholes, different strategies may be undertaken. One possibility, if the site is designed to accept all levels of waste, is to drill 75% of the deep boreholes, only those to be used for the placement of intermediate and low-level wastes that do not require canisters, and then allowing these wastes to be placed. Once these wastes are placed and the barriers and sealants installed, the site is re-opened for drilling of the final 25% of the large-diameter boreholes for the canister placement operations. In this way, crews can gain valuable experience in all aspects of safety, QA/QC, and operations before the more challenging activity associated with high level canister placement begins.

Although it seems a small detail, drill cuttings management facilities and sizing and blending facilities are needed if the drill cuttings (natural minerals) are to be used as part of the sealing materials, as recommended.

*Waste Placement and Closure*: We believe it is best if preparation of materials all be done in the general facilities area, and brought into the repository area only on demand. This applies to all sealants, barriers, casing, grouts, test materials, if needed, and so on. We recommend that a minimum of material be stored in the repository area, to avoid obstacles, and permit clear identification and QA/QC of all entering materials that are to be used. Unused materials should be returned immediately to the deployment and logistics areas outside the central repository, not locally stockpiled for days or weeks.

Waste placement, including waste entry by transport, placement in the borehole, and sealing, should take place only when no other technical activities are occurring on site. If maintenance activity is needed, such as regrading a section, building reconstruction, or other activity, waste placement should cease until these activities are terminated.

*Site Closure*: Site closure and remaining monitoring activity will be decided on during the active site operations, and no suggestions are made herein.

## 7.4 Repository Borehole Design and Execution

This section will appear repetitious because most of the issues and actions listed below have been partially dealt with in previous sections.

### 7.4.1 Basic Borehole Parameters

The large borehole depths, diameters, and designs (e.g., surface casing shoe depths) must be decided before guide hole drilling. Many possibilities exist, including the possibility of accepting the current scenario that we have used for preliminary assessment. Because of the modular nature of the approach we recommend, timing and costing of extended or altered designs will be straightforward. Here, we present some simple additional scenarios.

*Different Borehole Depths*: Assuming that the site will also be used for the placement of intermediate- and low-level wastes, one approach to be considered is to specify the number of boreholes to be used only for high-level wastes, and drill those boreholes deeper than the others. Consider the following option: assume thirty boreholes, 26 of which are drilled to 1000 m depth, accepting intermediate- and low-level wastes only in the bottom 300 m (the nature of the placement is to be decided). For a 600 mm diameter borehole, this number of boreholes can accommodate approximately 2200 m$^3$ of prepared wastes. How this converts to actual waste depends on the nature of the preparation.

Four boreholes only are designated for high-level waste. These holes are drilled to 2500 m depth, and with deviated drilling methods, offset at 10° outward inclination from vertical, except for the bottom 600 m, which is a vertical section encompassing the waste placement length. Assume that a canister is 400 mm in diameter and 1000 mm in length, and that each canister is to be placed no closer than 9 m to the previous canister in the borehole, with sealant/buffer isolation in-between. If the bottom 500 m are qualified for placement, this allows approximately 200 high-level waste canisters to be placed. Because retrievability remains an issue, these four holes are designed to allow re-entry by careful drilling or jetting using a coiled tubing unit, identification of sealant locations, markers, and so on, so that canisters can be re-attached, surrounding buffer material flushed out (coiled tubing unit with isolated pumping and return lines – double coiled tubing string so no uncontrolled returns to surface), and the canister lifted to surface.

Another possibility is that all boreholes are advanced to a greater depth than the 1 km scenario we have studied here. In that case, again assuming 2500 m depth, it is likely that for intermediate- and low-level wastes, a longer borehole interval would be sanctioned, perhaps the lower 1000 m, but only the lower 300 m for canister placement and sealing. Other designs are to be considered, depending on the pre-FEED decisions of the regulator and the DBP repository technical committee.

*Borehole Stability*: It is our opinion as rock mechanics experts that intact granites and very low porosity sedimentary rocks that are not intensely fractured with joints and de-bonded bedding planes can be drilled with water at 600 mm diameter and remain as stable, open boreholes to depths of 2000 m. A minor caveat to this opinion is the possible presence of unexpectedly high horizontal stresses at depth, and particularly the presence of highly anisotropic horizontal stresses. These values will be assessed during site qualification. For greater depths, or for larger diameters, it will be necessary to do a careful analysis and assessment of literature data to evaluate stability in the presence of high stresses and open-hole conditions.

### 7.4.2 Guide Hole Approach

Guide holes are drilled in the appropriate inclined trajectory to spread out the waste packages at the base of the boreholes. We recommend air/water hammer drilling with cuttings samples every one to two metres collected for mineralogical analysis or archiving. We recommend drill bit diameter to be approximately 100-125 mm, and that the guide hole bit be of a diameter that can accommodate a standard diamond drilling core barrel, in case coring is advised. We recommend that at this stage, a coiled tubing unit (see below) be available on site for packer tests, pump tests, and other investigative procedures for which the mining drilling rigs and the wireline systems are not as well equipped.

Decisions on whether or not there will be cored intervals depend on pre-FEED and FEED decisions, and these may be modified during operations if anomalies detected. One option is to core only the sections where canisters are to be placed. Many other options exist.

There may be some merit in advancing the guide hole 20 m deeper than the projected base of the large-diameter borehole, to examine the nature of the underlying rocks. However, this also creates a potential pathway that would have to be sealed for the high-level waste canister holes for security purposes, creating an additional set of activities to be carried out before waste placement. This is to be avoided if possible, but there may have to be pilot hole extension to well below the base of the projected borehole depths during the site qualification procedures, or during the pre-FEED activities, to better specify the GEM details.

### 7.4.3 Guide Hole Data and GEM Analysis

We recommend that a full suite of appropriate geophysical logs be executed for each guide hole for QA/QC purposes, for providing data to the GEM – the vitally important three-dimensional geological model – and for identification of any anomalous zones such as an unexpected fractured zone, an unexpected high natural flow rate zone, or an unexpected mineralogy interval. Each guide hole must include full televiewer or acoustic scanner information for identification of any joints that are sufficiently open to be identified as pathways. Other logs include density, natural gamma, quadrupole acoustic logs, and so on.

Decisions will have to be made as to the depth of logging. For example, the entire guide hole may be subjected to a standard suite of logs, but only the bottom interval where wastes are to be placed subjected to specialty logs such as a multi-receiver acoustic log that may help to identify local fractures through back-scatter analysis.

We note again that the final qualification of each hole for waste placement will take place only after all of the guide hole data are taken and analyzed for each hole and placed into the GEM for full site evaluation.

### 7.4.4 Mandrel Hammer Drilling of Large-Diameter Repository Boreholes

We recommend that air/water hammer large-diameter drilling of the repository boreholes be used, given the very brittle and dense nature of the rocks. A mandrel-equipped hammer drill will follow the precise trajectory of the guide hole. Figure 7-11 shows a mandrel-equipped hammer drill that could be used for construction.


*Figure 7-11: Mandrel-equipped hammer drill for extremely hard rocks (Courtesy: Center Rock Inc.)*

The conductor pipe hole can be drilled with a much smaller, easily moved drilling rig than the large-diameter holes needed for the surface casing and the repository borehole. There are many providers of such rigs for foundation engineering applications. Large-diameter deep boreholes will require heavy duty drilling rigs.

*Figure 7-12: Large-diameter reverse circulation equipped rig for blind-hole hammer drilling*

We recommend that drill cuttings be conserved and eventually size sorted to provide natural mineral filler to grouting and sealing materials that may be chosen. For example, if natural asphalt or a manufactured asphalt product (e.g., roofing tar) is used for sealing by placing it in a melted condition at appropriate intervals, adding 50% of the volume as sub-100 micron size inert mineral matter will reduce shrinkage on solidification, without impairing the sealing characteristics of the asphalt, and without introducing any reactive minerals. The remaining drill cuttings may form the basis of the aggregate and fine-grained material composition for any conventional backfills or seals that may be formulated to prove a surface cap to the boreholes

### 7.4.5 Potential Amelioration Approaches to Natural Fractures

The authors of this report are not experts in the sealing of natural fractures, but we are aware that there are many technologies that can be used to provide additional sealing activities (grouting) to natural factures that can accept some fluids. If natural fractures in the repository at depth are deemed worthy of additional sealing activities to reduce their natural conductivity levels, there are many options, and these options range from cementitious products to liquid silica grouts that precipitate silica in the joints, to low-viscosity polymer resins such as polyesters or epoxies. It is important that grouting take place at pressures well below any hydraulic fracturing pressures that could serve to open natural fractures.

## 7.5 Waste Canister Placement and Sealing

The specific physical nature of the wastes to be delivered to the site is not decided, except that canisters of some form will be used for high-level wastes. For high-level wastes, special considerations, buffer materials, and sealant barriers are necessary. For lower level wastes, different considerations apply. It is assumed that all wastes will be inert with respect to bacteriological activity, as the generation of methane (methanogenic archaebacteria) is to be avoided.

The nature of intermediate- and low-level wastes is such that container design will be substantially different than for high-level wastes, and we have deliberately used the term "capsule" to differentiate their containers from the HLW canisters. The simplest capsule design is perhaps a standard ("200 L") barrel of approximately 600 mm diameter and 850 mm length. (Note that this would require ≈750 mm diameter boreholes for emplacement.) These capsules would then be lowered into the borehole with wireline equipment and stacked one above the other. Although the upper part of the borehole would be rigorously sealed with non-deteriorating materials, the level of sealant in the capsule placement section would be minimal for low-level wastes.

For intermediate level wastes, aggressive compaction along with a cation absorbing material such as ground shale fragments and sealing in a carbon-fibre/epoxy capsule is a possible means of providing a geometry that is easily emplaced with wireline equipment. Different levels of sealing, encapsulation and barriers are to be considered for such materials.

The focus here is the approach to high-level canister placement, with steps taken to allow a high level of potential retrievability if recovery is mandated some time after closure. We assume that retrievability of intermediate- or low-level wastes would not be undertaken, but even then, it is feasible using reverse circulation rotary drilling technology or coiled tubing jetting to reopen repository boreholes, with the design of the capsules allowing retrieval. How to design and implement such a capsule for ILW and LLW wastes is not speculated upon here; the only issue is that if a retrievability mandate for ILW and LLW is adopted, it must be made possible through appropriate design.

We propose that canisters and sealing materials be placed using wireline hoisting methods and coiled tubing technology. These are extremely well-understood technologies in the O&G industry, and their use does not represent any significant novelty (a principle of repository creation). Methodologies for ILW and LLW capsule placements will also be stipulated during the FEED process.

### 7.5.1 Wireline Operations, Coiled Tubing Systems, and Remote-Controlled Options

We recommend that O&G industry wireline hoisting technology and coiled tubing units be used in the placement of canisters and the placement of the buffer and sealing materials. We also recommend that these systems be automated where reasonable and designed for remote control for certain operations that would involve close proximity to waste capsules or canisters, based upon calculations of exposure time and risk.

*Wireline Units*: The O&G industry has developed many downhole operations that can be carried out with wireline hoisting units, ranging from geophysical logging to lowering or retrieving heavy downhole systems.


*Figure 7-13: Weatherford Inc. wireline unit operating through a pressure control wellhead system (Courtesy: Weatherford International)*

Figure 7-13 shows a unit operating through a wellhead device that allows operations even if the well is an actively flowing well. The DBP repository boreholes will not be flowing (that would disqualify the site), and lowering canisters would take place through an open hole.

*Figure 7-14: High tensile strength composite wireline cable (courtesy: Schlumberger)*

Figure 7-14 shows a wireline cable with a hoisting capacity of 8000 kg to a depth of several thousand metres. Furthermore, power conduits in the centre portion allow electrical devices to be operated, and data transmission at extremely high rates to the surface. A waste canister of 400 mm diameter and 1000 mm length will have a mass no greater than several hundred kg (depending on the design), including the top hook for the wireline overshot system. Figure 7-15 shows an example of a canister design scenario, along with an image of a wireline overshot system to lower canisters. The same system could be used to retrieve the canisters at some future date.

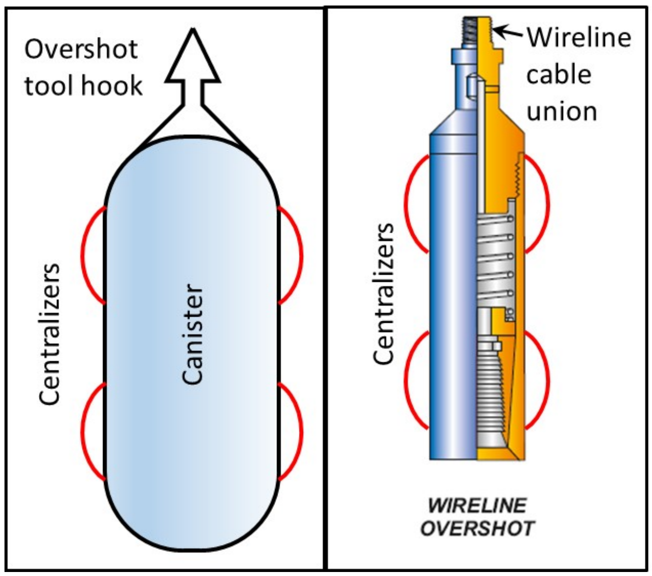


*Figure 7-15: Schematic of a canister and the connection system for hoisting*

Canister design itself is not part of the remit of this Report, but the borehole operations are. Each high-level waste canister should be equipped with a harness and an attached corrosion resistant overshot hook and centralizers, perhaps all fabricated from high-strength carbon-fibre epoxy (the hook must be radiation resistant as well if easy canister recovery is to be considered). The hook is designed to sustain a load of 10 times the mass of the canister in case it is necessary to pull the canister free of restraint. The centralizers are strong plastic composite springs that are deployed (electrically or mechanically) when the canister is placed at the hole bottom, to ensure that the buffer material is uniformly placed around the canister periphery, between the rock mass and the canister. Alternatively, if there is concern, the centralizers can be deployed fully during all wireline activities to prevent the canisters (and capsules) from sliding along the 10° borehole wall.

The wireline placement operation proceeds in the following fashion.

- The placement borehole integrity is fully verified by lowering a wireline gauge ring several mm smaller diameter than the hole size, to assure that there are no pieces of rock dislodged in the borehole wall or restrictions that could impair lowering.

- The wireline overshot device is attached to the canister hook and verified.
- Any electrical connection that will be used to release the hook, activate the centralizers, or perform any other function is verified.
- The canister is hoisted and lowered to hole bottom, with the tensile load on the cable precisely recorded throughout.
- Once on bottom, the centralizers are deployed, and their deployment is verified by a cable tensile load test (the centralizers increase the load by a small amount through friction) or other method.
- Any other electronic data are collected and transmitted to surface.
- The overshot hook is electrically released (this should be a double system to avoid accidental release at any other stage), and the system spooled back to the surface.

*Coiled Tubing Unit (CTU)*: An oilfield coiled tubing unit (CTU) is recommended as the system used to place buffer and sealant materials and conduct all downhole activities that involve the placement or removal of materials in liquid or slurry form. Also, the CTU can be equipped with all the necessary systems for down-hole packer tests, injection tests, resin grouting of zones, installation of various types of hardware (if any), vibro-compaction of granular backfill, and so on.

The CTU will have several strings available with different functions as needed. One of the strings will be a simple open tubing for placement of backfill, or for attachment on to testing systems (deep double-packer tests), another will be a double coiled tubing equipped to inject fluid by jetting through one bottom-hole port while returning the fluid through another (a "pump-to-surface" coiled tubing unit). Other specially designed strings can be built for specific activities.


*Figure 7-16: Coiled tubing units (Courtesy: Kruse Energy Auctioneers and STEP Energy Services)*

The top image in Figure 7-16 shows a standard CTU on a truck. The bottom image shows oilfield operations with a CTU, a pressure truck (left), the mast holding the blow-out preventers in place, and a pressure control/injection system for carrying out complex treatment fluid injection operations.

More compact, skid-mounted systems are available; an example of a simple version that uses smaller diameter tubing is shown in Figure 7-17. Systems and special spools are available for different diameter tubing.

*Figure 7-17: Skid-mounted small diameter coiled tubing reel (Courtesy: http://www.drillingformulas.com/coiled-tubing-equipment-overview/)*

The CTU approach is highly flexible, and, equipped with the correct systems, can achieve the following tasks associated with high-level canister placement at the repository site:

- Carrying out small-diameter borehole flow tests, installations, and sealing functions
- Placement of canisters if required (an alternative to wireline approaches)
- Placement of buffer material around each high-level waste canister after it has been lowered
- Placement of sealing material above each canister
- Placement of backfill material above the canister interval
- Lowering of vibro-compaction or other compaction equipment to densify granular backfill
- Placing of special sealing packers or mechanical bridge plugs within or above the canister system, if needed
- Slurrying and pumping out backfill material if this proves necessary
- Drilling out sealing materials or sealing packers
- Backflushing (jetting) and removal of buffer material above and around canisters
- Hooking and hoisting canisters to surface as an alternative to wireline systems
- …and many other tasks that are similar to deep borehole O&G activities

### 7.5.2 Borehole Sealing Material Issues

Spacing of canisters and sealing the boreholes containing high-level waste canisters are issues that must be decided based on many factors, many of these involving pathway probabilistic analysis and geochemical issues (adsorption, permeability, diffusivity, uncertainty) that are beyond the remit of this report. Nevertheless, because the major thrust is the integrity and use of the borehole in a mechanical sense, a set of comments is made. Figure 7-18 is conceptual only, the definitions of the spacing distances are not quantified, and many other possibilities will be investigated.

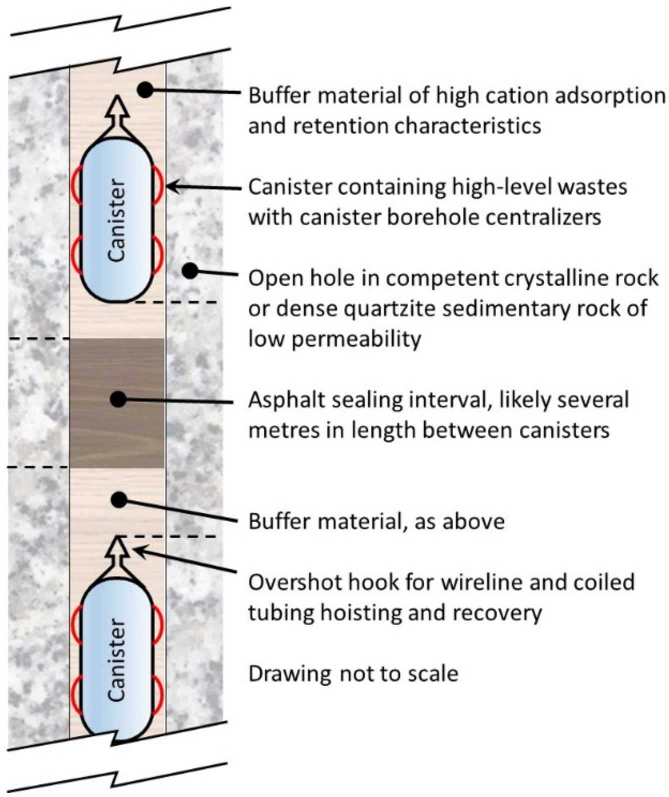


*Figure 7-18: A possible scenario for the disposition of buffer materials and sealing materials in a DBP borehole*

The placement boreholes will be created in dense, low permeability rock materials such as granites or very dense sedimentary rocks. We assume that the matrix permeability of the repository rock materials is deliberately and independently verified to be vanishingly small in the context of the other safety barriers and the natural rock mass conditions. We also assume that the geomechanics issue associated with pathway development are therefore associated with the potential for flow through natural fractures and the borehole. Therefore, the flow path assessment focus is to be on the natural facture systems and the borehole itself.

We believe that the following principles should be carefully examined and achieved in practice to assure that pathway development through the borehole or the borehole vicinity is highly improbable for high-level canister waste placement. Lower-level waste placement boreholes may have less stringent guidelines.

- Geochemically unstable metals and materials are to be avoided.
- Materials that could evidence long-term shrinkage are to be avoided.

- Any sealant material, buffer material, or backfill material should be, in principle, removable using reasonable effort to assure that the retrievability aspect is honoured.
    - All placed material should be readily removable through jetting or drilling.
    - All mechanical or inflatable packers (if used) or bridge plugs should be installed only with materials that are drillable with conventional practices using a coiled tubing drilling unit.
- Any locations along the large-diameter borehole with significant jointing patterns that have a potential for flow should be considered for deliberate sealing before canister placement occurs.
- In sealing and backfilling the borehole, any significant jointing locations, even if they have been pretreated by sealing, should be where ductile sealants are placed to further isolate the interval from the borehole materials.

*Buffer Material*: A high cation adsorption capacity material is considered part of buffer design principles to allow any cationic radionuclides to be adsorbed and thereby retarded from entering any potential flow paths. The annulus between the canister and the borehole wall is to be filled with buffer material, and this should be as densely placed as feasible to assure no shrinkage. The material should also be ductile rather than brittle, so that if loads arise, plastic deformation takes place, rather than brittle cracking, so that the permeability seal is maintained. Bentonite (smectite, montmorillonite) is commonly recommended and discussed in the nuclear waste placement literature. It may serve the purpose and can be placed appropriately with the coiled tubing unit. We mention here that other materials of high long-term geochemical stability could be considered, such as zeolites (Galamboš *et al*., 2012) and vermiculitic clay-shales (Dusseault and Scafe, 1979).

*Sealing Materials*: A ductile sealing agent is required, but the ductile sealant must not flow after placement, must be unequivocally stable, and must be easily placed. We advocate the use of natural asphalt (gilsonite) or a dense industrial asphalt because these can be melted in the borehole during placement to seal with the rock surface, because they retain ductility at the stresses of interest, because they are geochemically and bacteriologically inert, and because they do not react with any of the other materials used. The asphalt seals, or any other "setting" seal, can be used with inert filler materials. For example, 50% of the volume of an asphalt seal can be rock dust from the drilling (the fraction less than 100 μm), evenly dispersed in the asphalt

*Bridge Plugs - Packers*: Mechanical systems and packer systems can be installed to create positive pressure seals to the borehole, and these are widely used in the oil industry. If these systems are to be installed, they must be geochemically stable, non-reactive, and drillable.

#### 7.5.3 Backfilling the Borehole

We recommend that the drill cuttings from all boreholes be saved and used for assistance in the sealing activities and in particular the backfill section. The backfill section is the portion from above the last specific sealing material or sealing device to the surface. The cuttings can be sized (screened), reblended to make a very dense mix, and placed into the borehole using a variety of methods depending if the placement is to be in slurry or in granular form. A slurry liquid might be a specially formulated cement slurry, a dense aqueous slurry, or a slurry placed with a neutral mineral oil. Direct solid placement can be achieved as well through bail dumping, or other processes. Further densification can take place through vibro-densification during CTU placement, or even physical drop-weight compaction or vibro-compaction using a wireline hoist. Modest percentages of ground shale can be added to reduce permeability and provide additional absorptivity, and a series of mechanical seals (bridge plugs) or asphalt seals interspersed with the backfill.

We do not advise using a high-strength cementitious or resin impregnated backfill because this might impair retrievability. The backfill material should, in principle, be removable through using a dual tubing CTU system where a high-pressure jet erodes the backfill, which is pumped to surface.

#### 7.5.4 Additional Security Barriers and Design

The comments and recommendations herein may be extended, modified, or rejected if better methods of achieving secure barriers are developed.

#### 7.5.5 Borehole Closure and Capping

Each individual borehole should have a high-quality concrete placed into the last upper part of the borehole, within the surface casing, for the top 5-10 m. Thereafter, each borehole is capped with a suitable shield, perhaps even large granite blocks, suitably attached. Because the surface is sufficiently remote from the waste canisters at depth, the capping materials do not represent any additional flow path sealing contribution, and various options can be used, even eliminating the use of any obvious capping structure.

#### 7.5.6 Summary and Recommendations

We have outlined the major design and execution elements of a repository using the Deep Borehole Placement concept in dense rock. The major points are:

- Drilling uses mining equipment, and borehole stability to depths of 2 km will not be a concern.
- Waste canister placement, and placement of other levels of wastes using capsules, take place using wireline equipment, common to both mining and O&G industries.

- Buffer, sealant, and backfill placement take place with O&G equipment, specifically, coiled tubing technology.

All design elements are chosen to minimize the probability of generation of a pathway for fluid transmission of radioactive materials. Basic principles are:

- Materials that are not geochemically stable over millennia should not be used.
- All materials and the canisters should be removable and retrievable using well-understood equipment and procedures, and because borehole placement is being considered, the materials used for buffer, seal and backfill intervals must be drillable or otherwise recoverable.

To achieve a three-dimensional placement region of large volume and therefore low thermal footprint and waste material concentration footprint, we suggest an array of boreholes approximately as shown here, for a scenario involving 1000 m borehole depth (Figure 7-19).

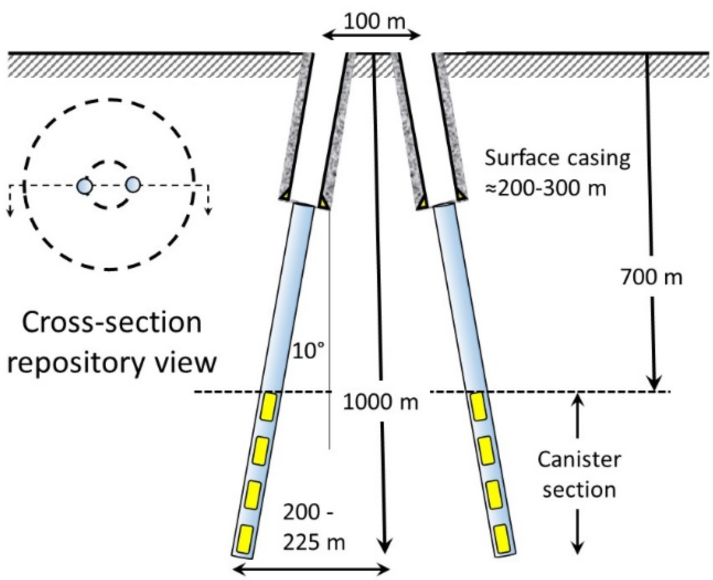


*Figure 7-19: Disposition of boreholes and canisters for a high-level DPB repository*

Each placement hole is deviated at an outward angle of 10° outward from the centre of the array. This means that the base of each hole is about 200-225 m from the vertical centre line of the repository. The dip angle of 10° outward from the centre assures that the bottom 300 m of each borehole is far from the centre, which makes the bottom 300 m, the high-level canister placement zone, laterally displaced for security, heat dissipation, and reduction of risks of interference between boreholes. Other boreholes may be used for placement of other levels of encapsulated radioactive waste.

# Chapter 8: Norwegian Geomechanics References

## 8.1 Overview of Geomechanics References

According to the London 1972 convention, waste will not be allowed to be stored offshore. The selected site will therefore be on land. The Norwegian offshore activities have however generated a great deal of knowledge which also applies onshore.

The Norwegian oil activity started around 1970 and has now been around for 50 years. During this period, more than 6000 offshore wells were drilled in Norwegian waters. All these wells have geological objectives in addition to the commercial oil objective. There has therefore been a considerable geological research in Norway, which is based on offshore measurements, but which also has improved onshore geological knowledge considerably. The offshore geology is therefore a prime candidate to establish onshore conditions for site selection.

Norway is located on the North-European plate which is relatively passive. In this chapter we will give a general view of Norway's geology, and we will present a few cases that appears relevant for the present project. These cases do not give the complete picture but are intended to be used to define criteria for site selection.

## 8.2 Geology of Norway

Because of the London Convention (Sjøblom and Linsley, 1992), offshore depositing of radioactive waste is ruled out. In the following we will give an overview of the geology of Norway, as a starting point for site selection. More detailed studies should be carried out as an extension of this report.

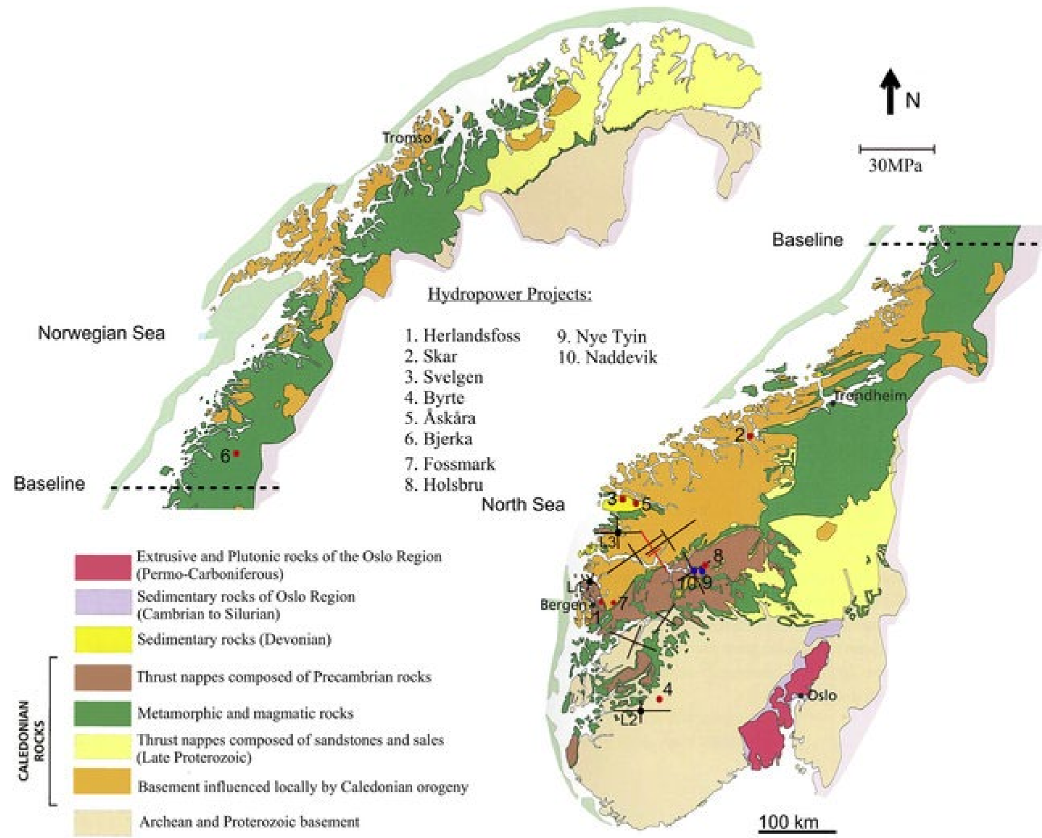


*Figure 8-1: Onshore geology of Norway (NGU, 2017)*

As seen from Figure 8-1 there is relatively little sedimentary rock covering Norway. The surface consists mainly of igneous and metamorphic rocks. If considering rock selection from a drilling perspective, there are many suitable locations.

## 8.3 Some Site Selection Criteria

There are many concerns for site selection, some of which are identified below.

- Proximity to humans. Obviously, a site should be away from the major cities. Southern Norway is most heavily populated and perhaps sites close to population centres should be ruled out. The Northern half of Norway is more sparsely inhabited, and might serve as a more suitable location from a population density aspect.
- There are many geological concerns. The most important is a location which is stable over long time; that is, away from large earthquake zones, regions of active tectonic movements, and areas where human activity could conceivably destabilize the geological environment (e.g. future drilling, mineral exploitation, waste injection…).
- The isolation area should not be permeable or severely fractured so as to minimize potential for pollution through flow pathways.

- Site selection should also consider the drilling process to minimize risks during placement of the canisters that might arise from hole condition.
- One key parameter is the stress state at the site. There are three likely scenarios, a normal fault stress state, a strike/slip fault stress state, and a reverse fault stress state (Anderson, 1951). Below we will address this issue from the perspective of minimizing the potential for leaks to surface.
- The context of long-term stability should be considered in a geological context knowing that Norway is located on the stable North European plate, in the Baltic Shield area. Within this plate there are several major Grabens such as the Central Graben and the Viking Graben. Also, there is a considerable number of low-level earthquakes, mainly offshore west of Norway. Referred to below is a study assessing stresses from earthquakes, although we acknowledge that these sources are offshore and unlikely to be of consequence to onshore activity or to the integrity of a DBP repository in strong, stiff rock masses.[58]

## 8.4 Crustal Stresses in Northern Norway

The tectonics and crustal stresses on-shore Norway have been studied and published extensively (e.g., Fejerskov and Lindholm, 2000) Early in the development of the oil industry offshore Norway it became evident that geomechanics was an important element. This was mostly related to wellbore stability such as fracturing and collapse of wellbores, but also sand production, subsidence, and reservoir compaction. In Norway, a strong geomechanics activity developed from the O&G industry, and this is also supported by a high level of tunnelling, military installations, and other rock mechanics activity involving crystalline or other stiff, brittle rocks.

The rock masses, especially the sedimentary sequences, vary continuously depth wise and there are relatively limited data available for deep cases onshore; most information is taken from well logs and pressure measurements in offshore wellbores. One key parameter is the magnitude and direction of the in-situ stresses. We commonly assume a vertical principal stress called the overburden stress and two horizontal stresses. These are difficult to assess but are indirectly estimated using various methods.

One of the main areas for oil production offshore Norway is the Tampen area just west of Bergen. It turns out that this is one of the most earthquake exposed areas in Northern Europe, releasing more than one hundred earthquakes each year. This represents the southern part of the Viking Graben. The North Sea includes two major grabens, the Central Graben between Norway and

[58] Earthquake damage is related largely to surface waves (Love and Rayleigh waves); at depth, it has been observed that structures such as tunnels are not highly susceptible to the body waves arising from non-local tectonic movements.

UK and the Viking Graben that extends west of Norway. Of course, the behavior of these structural features is affected by the stresses within the Northern Europe tectonic plate.

A project was established to see if relevant stress information could be obtained from earthquake focal mechanisms, and compare to data from the shallower wellbores.  In the following we will give a review of the results.

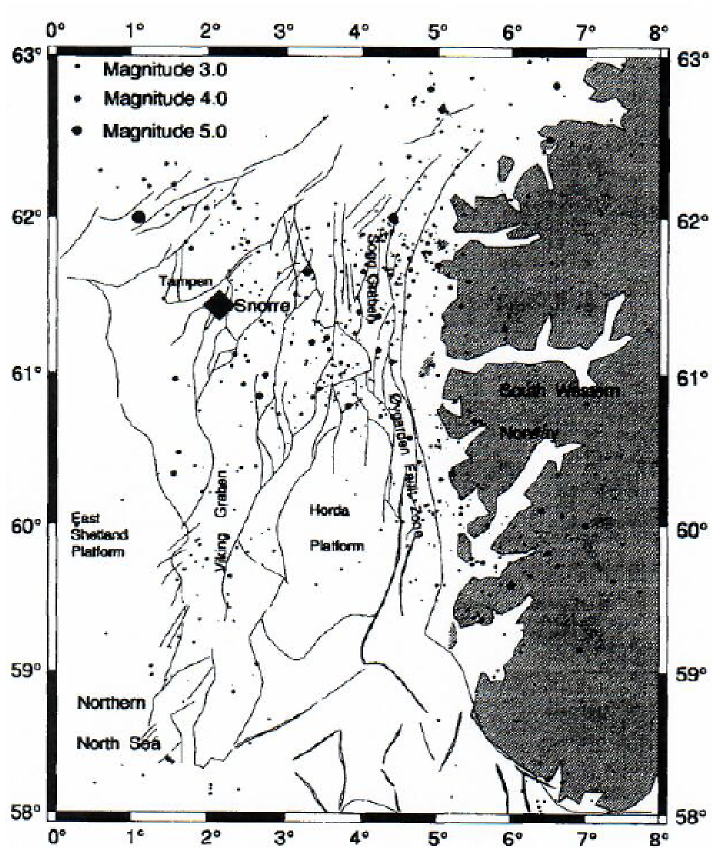


*Figure 8-2: Seismicity of the Northern North Sea for the time period 1984 to 1991. (Lindholm et al., 1995)*

Figure 8-2 gives an overview of seismic events during a 7-year period in the Northern North Sea. We observe that the largest earthquake has a magnitude of 5 on the Richter scale.  These earthquakes have a focal depth from 10 to 30 km with the majority being closer to 30 km depth. The seismic events were recorded at many seismic stations around the world and using these recorded events, a stress model was applied to estimate stress type and directions.

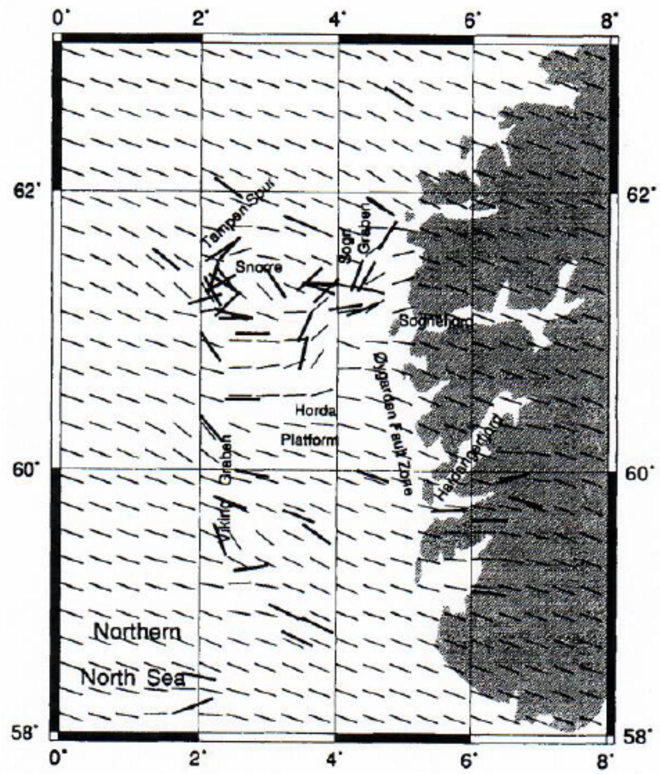


*Figure 8-3: Possible regional stress fields from seismic data. A boundary condition of 110 degrees applied at edges (Lindholm et al., 1995)*

Twenty sets of well data from the same area were collected and used in a comparative analysis. Wellbores often become elliptical due to the difference in in-situ stresses. The direction of the elongated hole is an indicator of the direction of the minimum horizontal in-situ stress. This is called a break-out analysis. Figure 8-4 summarizes the results of the break-out analysis in the Tampen area.

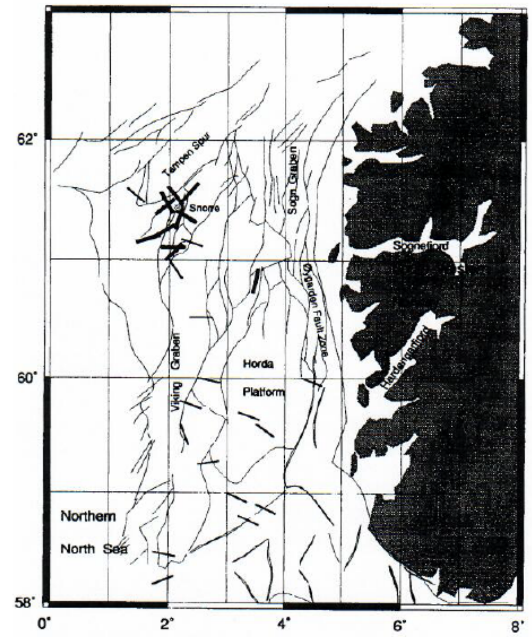


*Figure 8-4: Borehole breakout positions. The direction shown indicates maximum horizontal in-situ stress (Lindholm et al., 1995)*

A brief summary of the crustal stress analysis from Lindholm *et al*., (1995) is:

- Both borehole breakout analysis and earthquake focal mechanisms confirm that the regional compressive stress in the Northern North Sea is NW-SE oriented.
- There is good correspondence between shallow (2-5 km from breakouts) and deep (10-30 km from earthquakes) stress directions, and one can conclude that the stress direction is relatively constant through the crust.
- The earthquake focal mechanisms indicate an overall compressive stress with reverse faulting being most abundant.

The knowledge obtained from the enclosed analysis can be helpful in assessment of site selection and long-term risks.

## 8.5 High Stresses in the Barents Sea

The stress state in the North Sea is mostly a normal fault stress state to the Basal Cretaceous Unconformity (BCU), but at greater depth the stress state varies from place to place. The Norwegian North Sea is similar. However, in Northern Norway the situation is different. This was discovered when wells were drilled. In the following we will address this problem and also show the importance for radioactive waste placement.

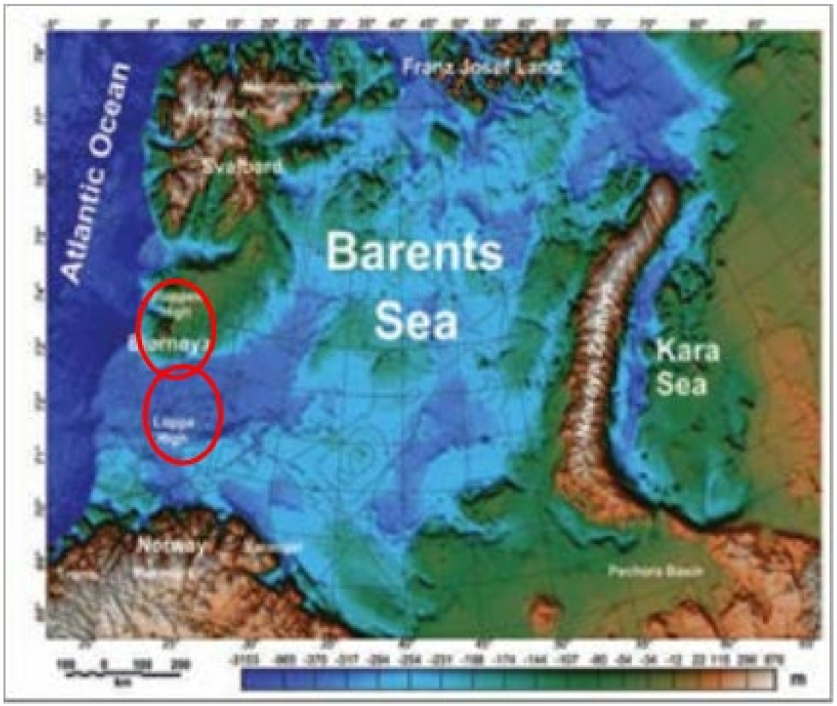


*Figure 8-5: Map over the study area (Aadnøy and Belayneh, 2018).*

The area of this study is shown in Figure 8-5. This part of Norway has in geologic time been exposed to denudation or erosion taking place slowly over tens of million to hundreds of million years. As much as 2 km of the seabed is eroded away, leaving earlier age rocks near the seabed.

During erosion the vertical stress is reduced, whereas the horizontal stresses are partially "locked-in". This creates an unbalance in stresses where the horizontal stresses exceed the overburden stress as erosion continues. This has effects on leaks as we discuss later.

Before discussion of the Norwegian data, we note that unusually high horizontal compressive stresses are common throughout the world in regions of slow uplift and erosion with highly competent rock, whether these areas were glaciated or not in the last few million years (Zang and Stephansson 2010). In the Underground Research Laboratory in Pinawa, Manitoba, extensive stress measurements in the granite pluton using various methods over many years of research confirmed a thrust regime at a depth of about 480 m below the surface (Haimson *et al.* 1993. More specifically, the vertical stress at this depth was determined to be the minimum principal stress at about 13 MPa, and the two horizontal stresses were estimated to be in a wide range of $\sigma_{HMAX}$ = 54 ± 13 MPa, and $\sigma_{hmin}$ = 36 ± 16 MPa. The observation that the maximum horizontal stress is four times larger than the vertical stress at this depth is important because it bespeaks of a large in-situ shear stress. Thermal perturbations or the establishment of mining rooms at this depth could lead to local shear displacements along existing joint surfaces or other planes of contrast in mechanical properties, faults, or more intensely fractured zones, generating larger apertures and increasing pathway generation probability. Hence, given that a Norwegian

DBP repository is likely to be sited in similar rocks (crystalline igneous rocks) that have experienced similar erosion histories over hundreds of millions of years, quantifying the stress state in the ground is a necessary aspect of site qualification.

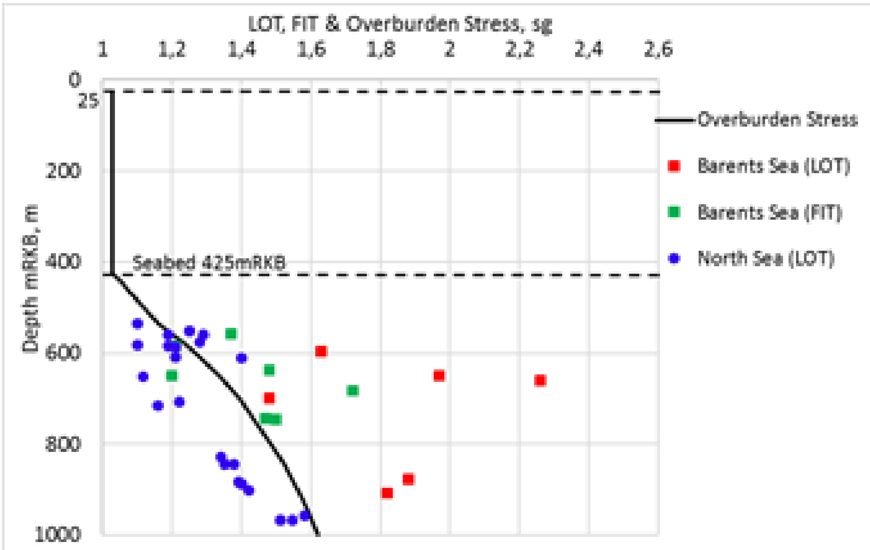


*Figure 8-6: Leakoff and formation integrity data from Barents Sea wells and North Sea wells (Aadnøy and Belayneh, 2018).*

In the Barents Sea, exceptionally high wellbore strength data as shown in Figure 8-6 are measured; the conclusion is that there must exist a higher in-situ horizontal stress state here than in the Norwegian North Sea sector. Furthermore, the in-situ stresses were computed as shown in Figure 8-7, showing consistently higher values than leak-off tests in the North Sea indicated. This is strong evidence that a so-called reverse fault (thrust) stress state exists in some areas, leaving the overburden as the minimum principal stress.

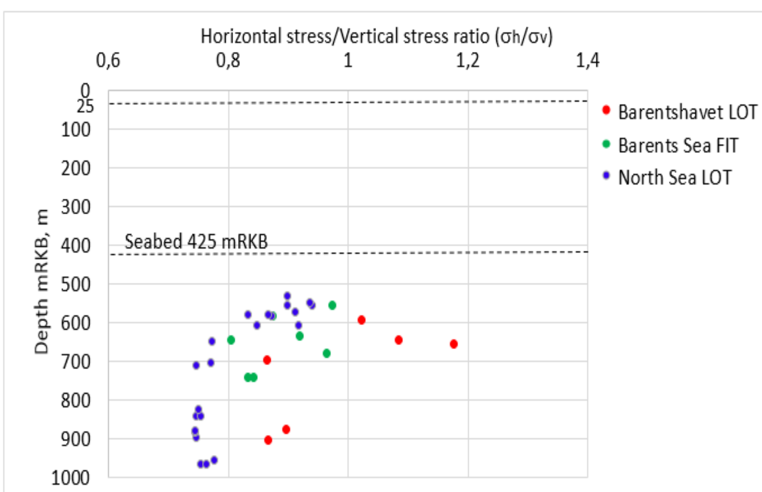


*Figure 8-7: Horizontal stresses to vertical stress ratio (From Aadnøy and Belayneh, 2018)*

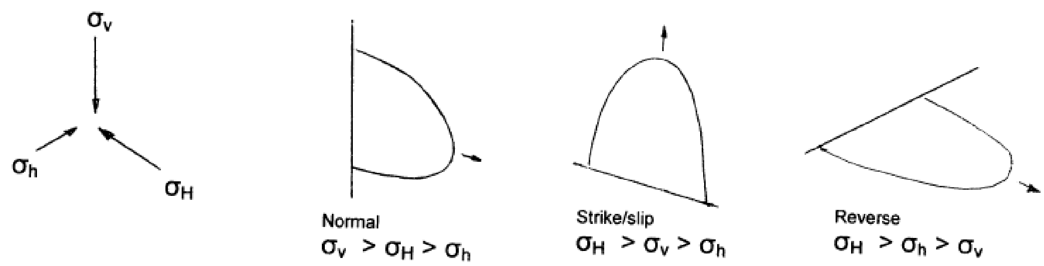


*Figure 8-8: Characteristic fracture directions for various stress ratio (Aadnøy and Looyeh, 2010).*

The three classical stress scenarios are:

- Normal fault stress state. Here the vertical overburden stress is largest. This stress state is common in the North Sea. An induced fracture will basically grow horizontally but also try to move upwards.
- Strike/slip stress state. Here the vertical stress is the intermediate stress. This is the worst situation as the fracture will grow directly upwards.
- The reverse fault stress state. Here the vertical stress is the minimum stress state. A fracture will grow horizontally as indicated.

Table 8-1 shows reported stress states from Scandinavia. The data shows that the typically observed stress state is that of a reverse fault stress state for all locations except Sulitjelma.

*Table 8-1: Reported stresses in Scandinavia (Brown & Hoek, 1978)*

| **Location** | **Rock-type** | **Depth (m)** | **$\sigma_V$ (MPa)** | **$\sigma_{h,av}/\sigma_v$** |
|---|---|---|---|---|
| Bleikvassli Mine, N. Norway | Gneiss and Mica Schist | 200 | 6.0 | 1.92 |
| Bleikvassli Mine, N. Norway | Gneiss and Mica Schist | 250 | 7.0 | 2.00 |
| Bleikvassli Mine, N. Norway | Pre-Cambrian rocks | 70 | 2.8 | 4.64 |
| Bjornevann, N. Norway | Gneiss | 100 | (2.7) | 5.56 |
| Sulitjelma, N. Norway | Phyllite | 850 | 10.0 | 0.99 |
| Sulitjelma, N. Norway | Phyllite | 900 | 11.0 | 0.55 |
| Stallberg, Sweden | Pre-Cambrian rocks | 915 | (24.7) | 1.56 |
| Vingesbacke, Sweden | Granite and amphibolite | 400 | (10.8) | 4.99 |
| Laisvall, Sweden | Granite | 220 | (5.9) | 3.72 |
| Malmberget, Sweden | Granite | 500 | (13.4) | 2.41 |
| Grangesberg, Sweden | Pre-Cambrian rocks | 400 | (10.8) | 2.31 |

| | | | | |
|---|---|---|---|---|
| Kiruna, Sweden | Pre-Cambrian rocks | 680 | (18.4) | 1.90 |
| Stalldalen, Sweden | Pre-Cambrian rocks | 690 | (18.6) | 2.58 |
| Stalldalen, Sweden | Pre-Cambrian rocks | 900 | (24.3) | 2.02 |
| Hofors, Sweden | Pre-Cambrian rocks | 470 | (12.7) | 2.74 |
| Hofors, Sweden | Pre-Cambrian rocks | 650 | (17.6) | 2.25 |

Furthermore, it is well established that reverse fault stress states exist inland Norway in crystalline rocks as shown in Table 8-1.

To summarize, a reverse fault stress state is preferable as an induced fracture from the possible generation of elevated pore pressures might be confined at depth with an accordingly low tendency for upward growth, whereas normal and strike/slip stress fault stress states are more inclined to allow upward fracture growth. One criterion for site selection could therefore be to look for reverse fault stress states, at least in the upper few hundred metres, which would act as an impediment to upward fracture flow. This is more probable in onshore crystalline rock sites that have experienced slow erosion over millions of years.

## 8.6 Oil in Fractured Basement Rock

Oil and gas are usually found in sedimentary rocks due to permeability and geologic history. Basement rocks such as granites and gneisses are typically impermeable and do not contain oil or gas. This is the common view, but the oil company Lundin has in recent years found a commercial oil field in a basement rock in the North Sea, something that was unthinkable a few years ago.

Already in 2011, they had a discovery in the basement of the Rolfsnes field. This has been further evaluated and is now moving into a commercial phase. The geological explanation is that the granite has been exposed to heavy rain and was intensely weathered millions of years ago, resulting in a heavily fractured granite which was later oil filled as the result of oil generation and migration.

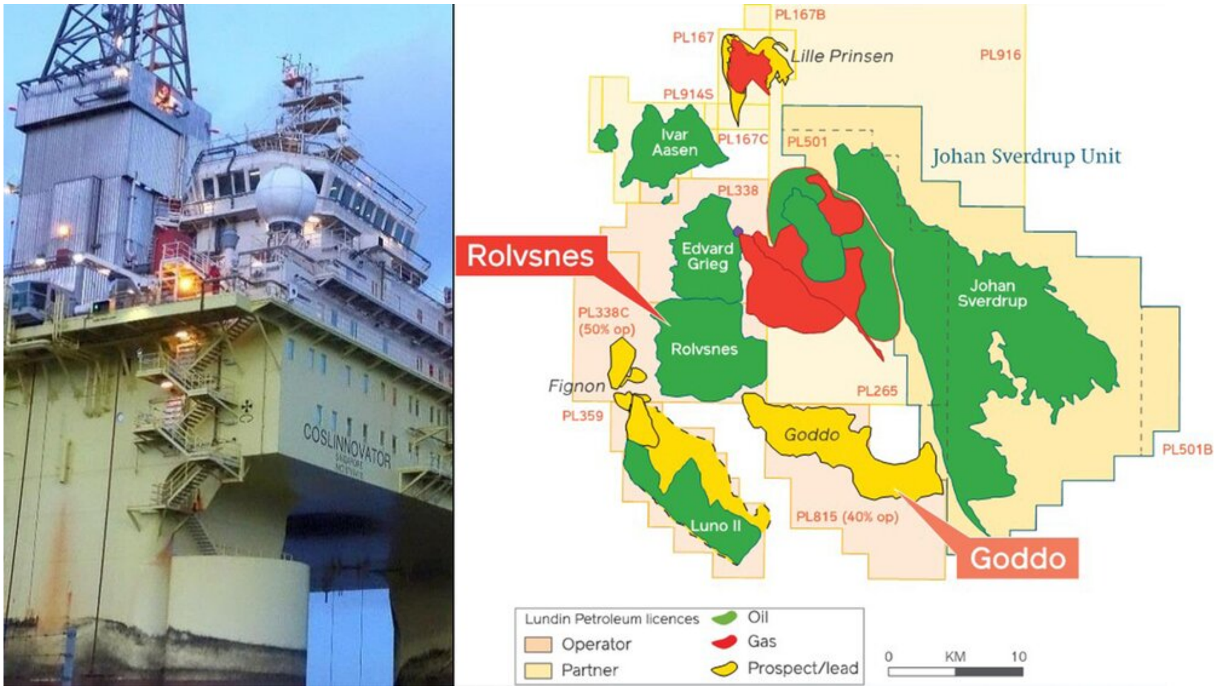


*Figure 8-9: Location of the Rolfsnes field with oil in fractured granite (Courtesy: Petroleum Safety Authority Norway))*

Oil companies avoid basement rocks and it would be of interest to find out if there were indications of fractured rocks on the seismic profiles, in which case it suggests that such intensely fractured zones can be detected before drilling.

The delineation of the condition of fractured granite is important for site selection for nuclear waste placement in a designed DBP repository. It is important to find a site with competent rock (widely spaced and tight or recemented natural fractures) to minimize the risks of leaks. Geological studies must identify likely locations and pilot holes must confirm the rock quality, stresses, and the conductive properties of the natural fractures.

## 8.7 Summary

This chapter gives a brief overview of Norwegian geology and addresses some important criteria for site selection. To summarize:

- Radioactive waste placement sites should preferably be in sparsely populated areas.
- As most of onshore Norway has igneous or metamorphic rocks to surface, this suggests that many sites could be suitable for DBP repository site selection.
- The North European plate and in particular the Baltic Shield is relatively static and stable at a million-year scale and should provide long-term safety for radioactive materials. Onshore Norway is away from the low-level earthquakes noted in the North Sea graben areas.

- Basement rocks provide good candidates for an isolation repository, but they can be fractured, so detailed fracture assessment must be done.
- Geomechanics analysis is essential, in particular in-situ stress assessment. It is proposed to favor a reverse fault stress state location, from the perspective of minimizing risks for leaks to surface.

## Chapter 9: References

Aadnøy, B.S. (2010) *Modern Well Design – Second Edition*. CRC Press, Taylor and Francis Group, London, UK. ISBN 978-0-415-88467-9.

Aadnøy, B.S. and Belayneh, M.A. (2018) High geostress advantageous for artic field development. OMAE2018-78629 presented at the *ASME 2018 37th International Conference on Ocean*, Offshore and Arctic Engineering, 17-22 June 2018/Madrid, Spain.

Aadnøy, B.S. and Looyeh, R. (2010) *Petroleum Rock Mechanics – Drilling operations and Well design*. Elsevier Gulf Publishing Company. ISBN 978-0-12-385546-6.

Anderson, E.M. (1951) *The dynamics of faulting and Dyke formation with Applications to Britain*. Oliver and Boyd, Edinburgh, UK, 206 pp.

Abelin, H., Birgersson, L., Gidlund, J., and Neretnieks, I. (1991) A Large-Scale Flow and Tracer Experiment in Granite: 1. Experimental Design and Flow Distribution. *Water Resources Research*, *27*(12), 3107–3117. https://doi.org/10.1029/91WR01405

Ahrens, E.H. and Onofrei, M. (1996) Ultrafine Cement Grout for Sealing Underground Nuclear Waste Repositories. *Rock Mechanics Tools and Techniques: Proceedings of the 2nd North American Rock Mechanics Symposium.* Montréal, Québec, v 2: 6 p. Taylor & Francis US.

Alexander, W.R and McKinley, L.E., Editors. (2007) *Deep Geological Disposal of Radioactive Waste*. Radioactivity in the Environment Series, Volume 9, Elsevier Amsterdam, ISBN-13: 978-0-08-045010-0

Arnold, B.W., Brady, P.V., Bauer, S.J., Herrick, C., Pye, S. and Finger, J. (2011) *Reference Design and Operations for Deep Borehole Disposal of High-Level Department Radioactive Waste*. US Department of Energy, Sandia National Laboratories, Report SAND2011-6749: 66 p.

Avis, J. and Kremer, E. (2017) Groundwater Transport of Radionuclides in a Crystalline Geosphere. Proc. Canadian Geotechnical Society Annual Conference GeoOttawa 2017, 8 p.

Barone, F., Stone, J., and Man, A. (2014) *Geotechnical Properties of Candidate Shaft Backfill*. Report by Golder Associates for the Nuclear Waste Management Organization. Report NWMO TR-2014-12, Available through the website of the Nuclear Waste Management Organization – NWMO - https://www.nwmo.ca/ 110 total pages.

Bates, E. A. (2015) *Optimization of deep boreholes for disposal of high-level nuclear waste.* Ph.D. Dissertation, Massachusetts Institute of Technology, Cambridge, MA.

Baumgärtner, J., Gérard, A. and Baria R. (2000) Soultz-sous-Forêts: Main technical aspects of deepening the well GPK2. *Proceedings World Geothermal Congress 2000*, Kyushu - Tohoku, Japan, 3653-3663.

Beswick, J. (2008) *Status of Technology for Deep Borehole Disposal*; NP 01185; Report by EPS International for the Nuclear Decommissioning Authority, UK; EPS International: London, UK.

Bhasin, R., Johansen, P.M., Barton, N. and Makurat, A. (2002) Rock joint sealing experiments using an ultra fine cement grout. Proc. North American Tunnelling Conf., Levent Ozdemir (ed.), CRC Press, Baton Rouge LA, 257-263, ISBN-13: 978-9058093769.

Bingen, B. and Solli, A. (2009) Geochronology of magmatism in the Caledonian and Sveconorwegian belts of Baltica: synopsis for detrital zircon provenance studies. *Norwegian Journal of Geology*, 89:267-290.

Bingen, B., Skår, Ø., Marker, M., Sigmond, E. M. O., Nordgulen, Ø., Ragnhildstveit, J., Mansfeld, J., Tucker, R. D. and Liégeois, J.-P. (2005) Timing of continental building in the Sveconorwegian orogen, SW Scandinavia. *Norwegian Journal of Geology*, 85:87-116.

Bram, K., Draxler, J., Hirschmann, G., Zoth, G., Hiron, S. and Kühr, M. (1995) The KTB Borehole – Germany's Superdeep Telescope into the Earth's Crust. *Oilfield Review*, 7:4-22.

Brady, P.V., Arnold, B.W., Freeze, G.A., Swift, P.N., Bauer, S.J., Kanney, J.L., Rechard, R.P. and Stein, J.S. (2009) *Deep Borehole Disposal of High Level Radioactive Waste*. US Department of Energy, Sandia National Laboratories, Report SAND2009-4401: XX p.

Brown, E.T and Hoek, E. (1978) Trends in Relationships between measured In-Situ Stresses and Depth. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr*. Vol 15, pp. 2011 – 205.

Bruno, M.S. (2006) *Fundamental Research on Percussion Drilling: Improved rock mechanics analysis, advanced simulation technology, and full-scale laboratory investigations*. US Department of Energy, DOE supported research project Percussion Drilling (DE-FC26-03NT41999), Terralog Technologies Inc., Monrovia, CA. 110 pages.

Brunskill, B. (2006) Discussion of an option for geological storage of used nuclear fuel beneath the Williston Basin of southern Saskatchewan; in *Summary of Investigations 2006*, v.1, Misc. Rep. 2006-4.1, Saskatchewan Geological Survey, Sask. Industry Resources, 8 p

Brush, L.H. (1990) *Test plan for laboratory and modeling studies of repository and radionuclide chemistry for the Waste Isolation Pilot Plant*. Report Number SAND-90-0266, Sandia National Laboratories, Albuquerque, New Mexico. OSTI #6927131; DOE/DP identifier ON: DE90013595; DOE Contract Number #AC04-76DP00789

Cai, M. and Kaiser, P.K. (2006) Visualization of rock mass classification systems. *Geotechnical and Geological Engineering,* 24: 1089–1102. DOI 10.1007/s10706-005-7464-x

Capouet, M., Carter, A., and Ciambrella, M. (2019) *International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste Version 30*. Retrieved from: http://inis.iaea.org/search/search.aspx?orig_q=RN:50061148

Černý, P., Fryer, B.J., Longstaffe, F.J. and Tammemagi, H.Y. (1987) The Archean Lac du Bonnet batholith, Manitoba: Igneous history, metamorphic effects, and fluid overprinting. *Geochimica et Cosmochimica Acta* 51(3): 421-438.

Clemens, T., Kienberger, G., Persaud, M., Suri, A., Sharma, M.M., Boschi, M. and Øverland, A.M. (2017) Optimizing Water-injection Design in a Shallow Offshore Reservoir. *SPE Production & Operations,* 14(2): 171-181.

CNSC. (2018) *Guidance on Deep Geological Repository Site Characterization* (REGDOC-1.2.1) Retrieved from: http://nuclearsafety.gc.ca/eng/acts-and-regulations/consultation/comment/regdoc1-2-1.cfm

Craciun, E., Zaharescu, T., Jipa, S., Mantsch, A., and Jitaru, I. (2011) Gamma Radiation Effects on the Stability of Epoxy Resin Modified with Titania Nanoparticles. *Materiale Plastice* 48(1):50 - 53

Crawford A.L. (1949) Gilsonite and Related Hydrocarbons of the Uinta Basin, Utah. Chapter, pp 235-260 in: *The Oil and Gas Possibilities of Utah*. Hansen, G.H. (ed.), Utah Geological and Mineral Survey, Salt Lake City, Utah, 341 p.

Darling, P. [Ed] (2011) *SME Mining Engineering Handbook*, 3rd edition. Two Volumes, ISBN#978-0-87335-264-2 1984 pages.

Davison, C.C., Brown, A., Everitt, R.A., Gascoyne, M., Kozak, E.T., Lodha, G.S., Martin, C.D., Soonawala, N.M., Stevenson, D.R., Thorne, G.A. and Whitaker, S.H. (1994) The Disposal of Canada's Nuclear Fuel Waste: Site Screening and Site Evaluation Technology, *Atomic Energy of Canada Limited Report, AECL-10713*, COG-93-3.

Deep Isolation Co. (2020) *Spent Nuclear Fuel Disposal in a Deep Horizontal Drillhole Repository Sited in Shale: Numerical Simulations in Support of a Generic Post-Closure Safety Analysis*. DI-2020-01-R0, Rev. 00, Berkley, California

Doe, T., Ingevald, K., Strindell, L., Haimson, B. and Carlsson, H. (1981) Hydraulic fracturing and overcoring stress measurements in a deep borehole at the Stripa Test Mine, Sweden. *Proc. 22nd U.S. Symposium on Rock Mechanics*, Massachusetts Institute of Technol., 6 p.

Doetsch, J., Krietsch, H., Schmelzbach, C., Jalali, MR., Gischig, V., Villiger, L., Amann, F. and Maurer, H. (2020) Characterizing a decametre-scale granitic reservoir using ground-penetrating radar and seismic methods. *Solid Earth*, 11:1441–1455, https://doi.org/10.5194/se-11-1441-2020

Drobne, S. and Lisec, A. (2009) Multi-attribute Decision Analysis in GIS: Weighted Linear Combination and Ordered Weighted Averaging. *Informatica*, 33: 459-474.

Dusseault, M.B., Isaacs, T., Leiss, W. (Chair), and Paoli, G. (2014) *Report of the Independent Expert Group on Risk Perceptions of the Four Alternative Means for Managing the Storage and Disposal of Low and Intermediate-Level Radioactive Waste in Ontario.*

Submitted to: The Joint Review Panel for the Deep Geologic Repository Project for Low and Intermediate Level Radioactive Waste (DGR). Available through the website of the Nuclear Waste Management Organization – NWMO - https://www.nwmo.ca/

Dusseault, M.B. and Jackson, R. (2014) Seepage pathway assessment for natural gas to shallow groundwater during well stimulation, in production, and after abandonment. *Environmental Geosciences,* 21(3):107–126.

Dusseault, M.B. and Scafe, D.W. (1979) Engineering and mineralogical index properties of the basal McMurray Formation clay-shales. *Canadian Geotechnical Journal*, 16(2):285-294

Fejerskov, M. and Lindholm, C. (2000) Crustal stress in and around Norway: an evaluation of stress-generating mechanisms. In Nøttvedt, A. *et al*. (eds): *Dynamics of the Norwegian Margin*. Geological Society, London, Special Publications, 167, 451-467.

Fink, J.K. (2012) *Petroleum Engineer's Guide to Oil Field Chemicals and Fluids*. Elsevier Inc. and Gulf Professional Publishing, 808 pages. ISBN 978-0-12-383844-5, https://doi.org/10.1016/C2009-0-61871-7

Fletcher, T. (1992) Drilling exploration boreholes beyond 4000 m in South Africa. *Mine Water and the Environment* 11:43–52.

Franca, L.F.P. (2011) A bit–rock interaction model for rotary–percussive drilling. *International Journal of Rock Mechanics and Mining Sciences* 48(5):827-835.

Franklin, J.A. and Dusseault, M.B. (1989) *Rock Engineering.* McGraw-Hill, New York, 600 p.

Franklin, J.A. and Dusseault, M.B. (1991) *Rock Engineering Applications*. McGraw-Hill, New York, 431 p.

Frape, S.K., Fritz, P. and McNutt, R.H. (1984) Water-rock interaction and chemistry of groundwaters from the Canadian Shield. *Geochimica et Cosmochimica Acta*, 48: 1617-1627

Freeze, G., Stein, E., Price, L., Mackinnon, R., and Tillman, J. (2016) *Deep Borehole Disposal Safety Analysis*. U.S. Department of Energy: Used Fuel Disposition, FCRD-UFD-2016-000075, Rev. 0, SAND2016-xxxxR

Freeze, G.A., Emily, S. Brady, P.V., Lopez, C., Sassani, D., Travis, K., Gibb, F. and Beswick, J. (2019) Deep Borehole Disposal Safety Case. *Energies*. 12, 2141, doi:10.3390/en12112141

Fuchs, K., Kozlovsky, Ye.A., Krivstov, A.I., and Zoback, M.D. [Eds] (1990) *Super-Deep Continental Drilling and Deep Geophysical Sounding*, Springer Science & Business Media, republished Dec. 6, 2012, 436 pages.

Galamboš, M., Suchánek, P. and Rosskopfová O. (2012) Sorption of anthropogenic radionuclides on natural and synthetic inorganic sorbents. *Journal of Radioanalytical and Nuclear Chemistry*, 293(2):613-633. https://doi.org/10.1007/s10967-012-1717-y

García, D., Grivé, M., Duro, L., Brassinnes, S. and de Pablo, J. (2018) The potential role of the degradation products of cement superplasticizers on the mobility of radionuclides. *Applied Geochemistry*, 98:1-9

Genter, A., Evans, K., Cuénot, N., Fritsch, D. and Sanjuan, B. (2010) Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of Enhanced Geothermal Systems (EGS). C.R. Geoscience 342, this issue; DOI: 10.1016/j.crte.2010.01.006.

Gérard, A., Genter, A., Kohl, T., Lutz, Ph., Rose, P. and Rummel F. (2006) The deep EGS (Enhanced Geothermal System) project at Soultz-sous-Forêts (Alsace, France). *Geothermics* 35:473-483.

Haak, V. and Jones, A.G. (1997) Introduction to special section: The KTB deep drill hole. *Journal of Geophysical Research*, 102(B8):18175-18177.

Haimson, B., Lee, M., Chandler, N. and Martin, D. (1993) Estimating the state of stress from subhorizontal hydraulic fractures at the underground research laboratory, Manitoba *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 30(7): 959-964

Hammami, A., Yakimoski, T., Craster, B. (Jr.) and Pearson, A.J. (2012) Fiber reinforced polymer oilfield tubulars and method of constructing same. Patent #US8123888B2 (Filed as US20090236091A1

Han, G., Bruno, M.S. and Dusseault, M.B. (2006) 3D Simulation of Rock Breakage with Air Hammers in Gas Well Drilling. *Proc. Gas Technology Symposium*, Calgary, Society of Petroleum Engineers Paper SPE #99522, 8 pages.

Hardin, E. L., Clark, A., Su, J., and Peretz, F. (2019) *Preclosure Risk Assessment for Deep Borehole Disposal.* Sandia National Laboratories. SAND2019-1827. Albuquerque, New Mexico.

Harms, U., Koeberl, C. and Zoback, M.D. [Eds] (2007) *Continental Scientific Drilling: A Decade of Progress, and Challenges for the Future*, Springer Science & Business Media, 366 pages

Harrison, T. (2000) Very deep borehole concept: Deutag's opinion on boring, canister emplacement and retrievability. SKB, May. ISSN 1402-3091, SKB Rapport R-00-35, 56 pages

Häring, M.O., Schanz, U., Ladner, F. and Dyer, B.C. (2008) Characterization of the Basel 1 enhanced geothermal system. *Geothermics*, 37:469-495.

Haug, K., Nygaard, R. and Keith, D. (2007) Evaluation of stress and geomechanical characteristics of a potential site for $CO_2$ geological storage in central Alberta, Canada. Proceedings, Ottawa 2007 Canadian Geotechnical Conference, 8 p. Retrieved from: https://scholar.harvard.edu/files/davidkeith/files/109.haug_.2007.evalofstressgeomchar.e.pdf

Hutcheon, I. (1998) The Potential Role of Pyrite Oxidation in Corrosion and Reservoir Souring. *Journal of Canadian Petroleum Technology*, 37(1): https://doi.org/10.2118/98-01-05

IAEA (2011) *BOSS: Borehole Disposal of Disused Sealed Sources – Technical Manual*. IAEA-TECDOC-1644.

Intera (2008) *Phase 2 Geoscientific Site Characterization Plan: OPG's Deep Geologic Repository for Low and Intermediate Level Waste*. OPG 00216-REP-03902-00006-R00. Available on the Nuclear Waste Management Organization's website: https://www.nwmo.ca/

Ji Shaocheng & Xu Zhiqin [Eds] (2009) The Chinese Continental Scientific Drilling. Special Issue of *Tectonophysics*, 475(2):201-414.

Kemna, A., Binley, A. and Slater, L. (2004) Crosshole IP imaging for engineering and environmental applications. *Geophysics*, 69(1): 97–107. DOI:10.1190/1.1649379

Khalifeh, M. and Saasen, A. (2019) *Introduction to Permanent Plug and Abandonment of Wells*. Springer Nature, Switzerland. Retrieved from: https://link.springer.com/book/10.1007%2F978-3-030-39970-2

Kozlovsky, Ye.A. [Ed] (1987) *The Superdeep Well of the Kola Peninsula*, Springer Science & Business Media, republished Dec. 6, 2012, 558 pages

Kraft, M.E. and Clary, B.B. (1991) Citizen Participation and the Nimby Syndrome: Public Response to Radioactive Waste Disposal, *The Western Political Quarterly*, 44:299-328. DOI: https://doi.org/10.1177/106591299104400204

Larkin, P., Gracie, R., Shafiei, A., Dusseault, M.B., Sarkarfarshi, M., Aspinall, W. and Krewski, D. (2019) Uncertainty in risk issues for carbon capture and geological storage: findings from a structured expert elicitation, *Int. J. Risk Assessment and Management*, 22(3/4): 429–463.

Lindholm, C.D., Bungum, H., Bratli, R.K., Dahl, N., Tørudbakken, B. and Aadnøy, B.S. (1995) Crustal stress in the Northern North Sea as inferred from borehole breakouts and earthquake focal mechanisms. *Terra Nova*, 7,1. Blackwell Science Ltd, 1995.

Linkov I., Satterstrom F.K., Kiker, G., Batchelor, C., Bridges, T., and Ferguson, E. (2006) From comparative risk assessment to multi-criteria decision analysis and adaptive management: Recent developments and applications. *Environment International*, 32: 1072-1093. doi:10.1016/j.envint.2006.06.013

MacKinnon, R., Freeze, G., Perry, F., Tarabay, A., Homel, M., Calvo, R., and David, O.K. (2018) *Deep Borehole Disposal in Israel.* Albuquerque, NM: Sandia National Labs

Mandl, G. (2005) Rock *Joints, The Mechanical Genesis*. Springer-Verlag, Berlin Heidelberg, 231 p.

MIT (Massachusetts Institute of Technology), (2006) *The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century*. Boston: MIT Press.

Nadeem, M. and Dusseault, M.B. (2007) Geological engineering criteria for deep waste disposal. *Environmental Geosciences* 14(2): 61-77.

Nirex (2004) A *Review of the Deep Borehole Disposal Concept*. Nirex Report N/108. United Kingdom: Nirex Limited.

NORSOK (2013) *Well integrity in drilling and well operations* (D-010). Rev.4, Standards Norway: Norway

NWMO (2011) Report – *Environmental Impact Statement, Vol 1*. Part of the Nuclear Waste Management Organization's commissioned investigations of the potential Deep Geological Repository site in Ontario at the Bruce Nuclear Site (00216-REP-07701-00001 R000). All reports available through https://www.nwmo.ca/

NWMO (2017) *Postclosure Safety Assessment of a Used Fuel Repository in Crystalline Rock*. TR-2017-02. Available through the website of the Nuclear Waste Management Organization – NWMO - https://www.nwmo.ca/ 719 total pages.

O'Brien, M.T, Cohen, L.H., Narasimhan, T.N., Simkin, T.L., Wollenberg, H.A., Brace, W.F., Green, S. and Platt, H.P, (1979) *The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste Disposal*. Lawrence Berkeley Laboratory, Berkeley, California

Oglesby, K.D. (and cooperating entities and researchers), (2014) *Deep Geothermal Drilling Using Millimeter Wave Technology*, Final Technical Research Report, 206 p. Project Number: DE-EE0005504; DUNS Number: 141810494, Retrieved from: https://www.osti.gov/servlets/purl/1169951

Pletcher, J.P. II, Scarr, A., Smith, J., Swadi, S.N. and Rogers, C. (2010) Application of Air Percussion Drilling Improves Drilling Efficiency in Horizontal Sandstone Wells. *Proc. SPE Annual Technical Conference and Exhibition*, Florence, Italy. SPE-135308-MS, 17 pages.

Polsky, Y., Capuano L., *et al.* (2008) *Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report*, Sandia Report SAND2008-7866.

Price, N.J. (1959) Mechanics of Jointing in Rocks. *Geological Magazine*, 96(2):149-167. DOI: https://doi.org/10.1017/S0016756800060040

Pusch, R. (2008) Geological *Storage of Highly Radioactive Waste: Current Concepts and Plans for Radioactive Waste Disposal*. Springer-Verlag, Berlin: xix + 379 p.

Pusch, R., Ramqvist, G., Kasbohm, J., Knutsson, S. and Mohammed, M.H. (2012) The Concept of Highly Radioactive Waste (HLW) Disposal in Very Deep Boreholes in a New Perspective. *Journal of Earth Sciences and Geotechnical Engineering*, 2(3): 1-24. ISSN: 1792-9660

Rechard, R.P., Freeze, G.A. and Perry, F.V. (2014) Hazards and scenarios examined for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. *Reliability Engineering and System Safety,* 122: 74-95.

Regener, T., Reich, M., Duerholt R. and Wagner B. (2005) Latest Positive Displacement Motor and Drill Bit Developments for Drilling Hard and Abrasive Formations., *Proc. SPE/IADC Drilling Conference*, Amsterdam, Society of Petroleum Engineers Paper SPE-92542-MS, 10 pages.

Saasen, A. Wold, S., Ribesen, B.T., Tran, T.N., Huse, A., Rygg, V., Grannes, I. and Svindland, A. (2011) Permanent Abandonment of a North Sea Well Using Unconsolidated Well-Plugging Material. *SPE Drilling & Completion Journal*, 26(3): 5 p. SPE #133446, DOI: https://doi.org/10.2118/133446-PA

Sanfillippo, F., Brignoli, M., Santarelli, F. J. and Bezzola, C. (1997) Characterization of Conductive Fractures While Drilling. *Proc. SPE European Formation Damage Conference*, The Hague, Netherlands. Society of Petroleum Engineers SPE-38177-MS, 10 p. DOI:10.2118/38177-MS

Sjöberg, L. (2003) The Different Dynamics of Personal and General Risk. *Risk Management* 5: 19–34.

Sjöberg, L. and Drottz-Sjöberg, B.M. (2001) Fairness, risk and risk tolerance in the siting of a nuclear waste repository, *Journal of Risk Research*, 4(1): 75-101, DOI: https://DOI.org/10.1080/136698701456040

Sjøblom, K.L. and Linsley, G. (1994) Sea disposal of radioactive wastes: The London Convention 1972. *IAEA Bulletin*, 2/1994, pp. 12-16.

Sousa, L.M.O. (2007) Granite fracture index to check suitability of granite outcrops for quarrying. *Engineering Geology*, 92:146-159. DOI: 10.1016/j.enggeo.2007.04.001

Surma, F. and Geraud, Y. (2003) Porosity and Thermal Conductivity of the Soultz-sous-Forêts Granite. *Pure and Applied Geophysics*, 160:1125–1136. 0033 – 4553/03/061125–12

Taugbol, K., Gunnar, F., Prebensen I.O., Kaare, S., Omland, T.H., Svela, P.E. & Breivik, D.H. (2005) Development and Field Testing of a Unique High Temperature and High Pressure (HTHP) Oil Based Drilling Fluid With Minimum Rheology and Maximum SAG Stability. *Proc. Society of Petroleum Engineers Offshore Europe Oil and Gas Exhibition and Conference*, 6-9 September, Aberdeen, UK, SPE-96285-MS, 9 p. https://doi.org/10.2118/96285-MS

Trotignon, L., Devallois, V., Peycelon, H., Tiffreau, C., and Bourbon, X. (2007) Predicting the long-term durability of concrete engineered barrier in a geological repository for radioactive waste. *Physics and Chemistry of the Earth*, 32: 259–274

van Oort, E., Ripley, D., Ward, I., Chapman, J.W., Williamson, R. and Aston, M. (1996) Silicate-Based Drilling Fluids: Competent, Cost-effective and Benign Solutions to Wellbore Stability Problems. *Proc. SPE-IADC Drilling Conference*, New Orleans, LA, SPE #35059, 16 p. DOI https://doi.org/10.2118/35059-MS

Wang, D., W. Zhang, X. Zhang, G. Zhao, R. Zuo, J. Ni, G. Yang, J. Jia, K. Yang, Y. Zhu, W. Xie, W. Zhu, P. Zhang, L. Fan, J. Ye and Y. Wang. (2015) *The China Continental Scientific Drilling Project: CCSD-1 Well Drilling Engineering and Construction*. Springer.

Weisenberger, T.B., Hardarson, B.S., Mesfin, K.G., Einarsson, G.M., Nielsson, S., Sierenberg, R.A. and Fridleifsson, G.O. (2019) The Iceland deep drilling project at Reykjanes - 4.5 km deep drilling into supercritical conditions. *Proceedings in 44$^{th}$ Workshop on Geothermal Reservoir Engineering* 11 SGP-TR-214.

Williams, B.K., Brown, E.D., and 36 other contributors. (2012) Adaptive *Management*. US Department of the Interior Applications Guides. x + 120 pages, ISBN 978-0-615-59913-7.

Winterle, J., Pauline, R. and Ofoegbu, G. (2011) *Regulatory Perspectives on Deep Borehole Disposal Concepts*. Prepared for U.S. Nuclear Regulatory Commission, Contract NRC–02–07–006. Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas, i-vi + 28 pages.

Wittig, V., Bracke, R. and Hyun-Ick, Y. (2015) Hydraulic DTH Fluid / Mud Hammers with Recirculation Capabilities to Improve ROP and Hole Cleaning for Deep, Hard Rock Geothermal Drilling. *Proc. World Geothermal Congress 2015*, Melbourne, Australia, 9 pages.

Yesiloglu-Gultekin, N., Gokceoglu, C. and Sezer, E.A. (2013) Prediction of uniaxial compressive strength of granitic rocks by various nonlinear tools and comparisons of their performance. *International Journal of Rock Mechanics and Mining Sciences*, 62:113-122

Xie, Xiyang (2019) *Time-dependent deformation of rock around a borehole: Shale as a permanent barrier after well abandonment.* Thesis presented in partial fulfillment of the requirements for the PhD degree in Engineering, Norwegian University of Science and Technology (Norwegian: Norges teknisk-naturvitenskapelige universitet, NTNU), 273 p.

Zang, A. and Stephansson, O. (2010) *Stress Field of the Earth's Crust*. Springer-Verlag, Berlin Heidelberg, 324 p.

Zoback, M.D., Hickman, S. and Ellsworth, W. (2011) Scientific drilling into the San Andreas Fault zone – An overview of SAFOD's first five years. *Scientific Drilling* 11(1):14-28.

## Appendix I: Proposal for a DBP Test Facility

Bernt Aadnoy, Stavanger University, Norway

Maurice Dusseault, University of Waterloo, Ontario, Canada

### Premise

A secure repository for nuclear waste in Norway could involve Deep Borehole Placement (DBP) in high quality rock masses. Before Repository Site Selection (RSS), Site Qualification (SQ) and Front-End Engineering and Design (FEED) activities take place, a full-scale demonstration of the technical feasibility of the basic design concept should take place. This demonstration project will allow the testing of site investigation methods, drilling methods, and waste placement methods. Furthermore, such a project will help verify a number of findings and assumptions made in the context of world-wide repository studies in dense rock in Canada, Sweden, Finland, Korea, and other places.

### Repository Options in Norway

Assessment of options and prioritization of choices for radioactive waste sequestration is a necessary activity once a decision is made to isolate these wastes in a secure manner. All viable options involve the geosphere in some way (Pusch 2008; Alexander and McKinley 2007), from a surface facility to a mine concept to a DBP option. Hence, geosphere options must be addressed in the Norwegian context.

Offshore placement of high-level reactor wastes in North Sea sediments is not a permitted option. Placement in a shallow subsurface repository (e.g., a reinforced concrete bunker) is not considered sufficiently secure. Norway lacks thick sequences of suitable, undeformed sedimentary rocks onshore that would accept deep boreholes for placement: even the thickness of flat-lying Paleozoic sediments in northern Norway is not great, and partially undefined as to their suitability. For example, NWMO in Ontario, Canada has identified 670 m deep undeformed Paleozoic sediments of low porosity, found in an excellent hydrogeological disposition, as a viable repository site for power reactor wastes of an intermediate and low level (e.g., many technical studies at https://www.nwmo.ca/ ). Currently, fuel sequestration options in hard crystalline rock are being investigated in Canada. There are no onshore deposits in Norway of halite (NaCl), such as those used in the WIPP facility in the USA (e.g., Brush 1990), and extensively studied by many countries (Germany, USA).

Thus, it appears that there are two viable geosphere repository options:

- A mine-and-placement-room concept, placed in competent crystalline igneous rock or in suitable dense sediments
- A Deep Borehole Placement concept, with wastes placed in boreholes created in competent crystalline igneous rocks or suitable dense sediments

Given that the total volume of high-level wastes to meet the Norwegian need is small, compared to countries that have large investments in nuclear power generation, the highly expensive infrastructure of a deep mine repository is an economic burden. Mining industry and oilfield industry technologies are highly advanced, reliable, and reasonable in cost: this suggests that placement of wastes in a highly secure manner in deep boreholes in a high-quality rock mass, suitable located, is a highly probable and technically viable option.

We believe that a DBP repository is the most reasonable option for Norway to pursue. This option is modular (only as many boreholes as needed), costs are roughly linear with the number of boreholes, security level is demonstrably very high, and much of the technology is available directly in Norway.

**<u>The Full-Scale Demonstration</u>**

We propose a full-scale demonstration of material placement and sealing in a large-diameter borehole to prove the DBP concept at the appropriate level at this time. This project can follow the phases outlined in the DBP repository Report upon which this proposal is based (Dusseault and Aadnøy 2020). The reasons for a full-scale demonstration can be summarized as follows:

- Proof-of-concept at full scale (1 km deep borehole, 80° dip, 600 m diameter)
- Testing the methodologies for SQ in adjacent small diameter pilot boreholes, including full-length coring, testing and instrumentation, cross-hole seismics, surface seismics, borehole pressure testing devices, stress measurements, etc.
- Testing the guide hole directional drilling (10° inclination from vertical)
- Testing the wireline and coiled tubing methods for canister/capsule placement, sealing and backfilling
- Outlining the major aspects to be covered in the FEED process for establishing the design and implementation of a multi-borehole DBP repository
- Test various methodologies, including, among others, the following:
    - Use of asphalt with mineral flour as a sealant with thermal (melting) placement, if such a material has been deemed able to provide long-term safety
    - Develop a buffer material design and placement method to meet the defined needs
    - Canister harness design, placement methodology and recovery approach using a wireline overshot system
    - Buffer, sealant, plug and backfill placement, including densification, with a coiled tubing unit
    - Demonstrate retrievable canister concept

We also point out that in addition to the technical issues, data collection, testing of various methodologies, etc., the demonstration project will also provide opportunities for training of highly qualified persons (HQPs). These will become resources and employees for the full-scale project and raise the level of Norwegian capabilities to the world level in an interesting area. The project will provide opportunities for testing of novel devices (sensors, downhole tools), methodologies (flow testing wireline tool use), and concepts (buffer and sealant design and placement) that need study.

Such a demonstration site could also, eventually, become a site for waste placement, assuming that the site meets all of the qualification criteria. The full-scale demonstration site could therefore be planned for development at the chosen DBP repository site, and the demonstration borehole kept as a testing and training facility as other boreholes are developed and waste placed. The DBP Test Facility borehole would continue to be used to qualify procedures, materials and personnel on an on-going training and quality control program, adding to the security of the entire process.

**The Demonstration Project Team**

The writers have expertise in mining and oilfield technology of various types including drilling, workover approaches, wireline methods, stress measurements, and many related issues. We have strong engineering geology, geomechanics, thermo-geomechanics, and coupled thermohydromechanical mathematical simulation backgrounds. The Demonstration Project for the DBP repository concept will require an integrated team that also includes geophysicists, geochemists, laboratory specialists, instrumentation specialists, and other sources of expert input.

We note that the project will further foster the advancement of good subsurface science in Norway, and be an excellent demonstration project for repository work around the world. We note that Norway has excellent companies for operations, advisory work, and technology, and this DBP Test Facility and the DBP repository are suitable national projects. Although some external expert advice is suitable, the vast majority of the project is completely manageable with national sources.

**Proposal**

We propose that the full-scale DBP demonstration project be developed as a science and engineering project for advancement of methodologies and materials in the subsurface in Norway. The well educated workforce in Norway is quite capable of providing all of the highly skilled personnel for all aspects of the full DBP repository project.

Part of our proposal is that the site qualification procedure take place in a manner very similar to the methodology proposed in the Report, constituting a full-scale study, not a reduced model study.

We believe that the scenario discussed in the report – a 1 km deep ≈600 mm diameter hole, inclined 10° from the vertical, be the actual scenario used in the demonstration project. The first figure below shows the general design of a single borehole, and we will recommend a 10 m deep conductor pipe and a 200 m deep surface casing, each requiring larger diameters than 600 mm.

The next figures show the demonstration project layout at the surface as well as the cross-section view of a 10° inclined borehole. Several test holes (#1, #2, #3) will be drilled to emulate the site qualification procedure and test out devices such as wireline packer tests, stress measurements (overcoring), specialty geophysical logging devices, cross-hole seismic, and sensor placement. One pilot hole is drilled parallel to the large diameter test borehole, for use in testing flow intercommunication.

The next stage is to commission a more detailed plan for a demonstration project.

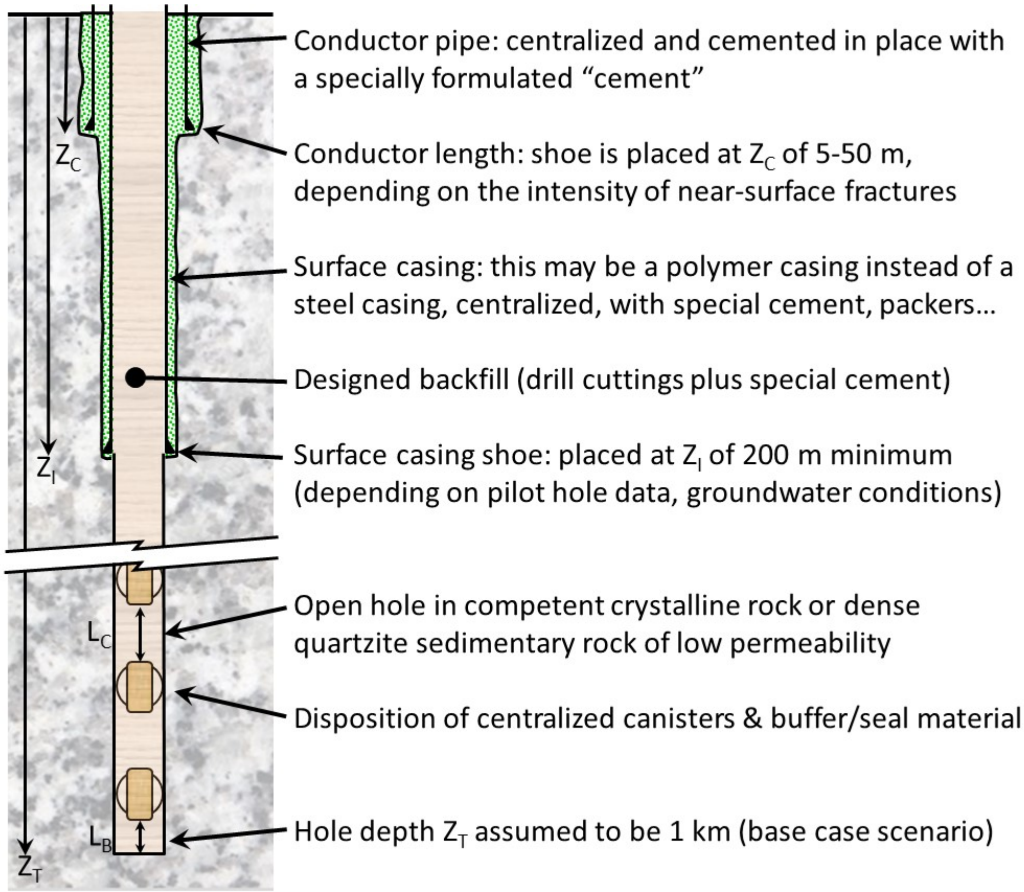


*Figure I-10: The basic design for a large diameter deep borehole for placement of radioactive waste*

A question arises as to whether a full-scale test facility should be established at the site for the actual DBP repository, and the DBP Test Facility boreholes eventually become waste disposal boreholes. Because the DBP Test Facility borehole may be subjected to many trials and experiments, and because it will therefore likely be more heavily monitored with sensor boreholes, this possibility should be assessed carefully before doing this. Perhaps such a test borehole would be limited to intermediate-level waste placement if there was any concern that it would be of lower functional quality after the experimentation and technology practice.

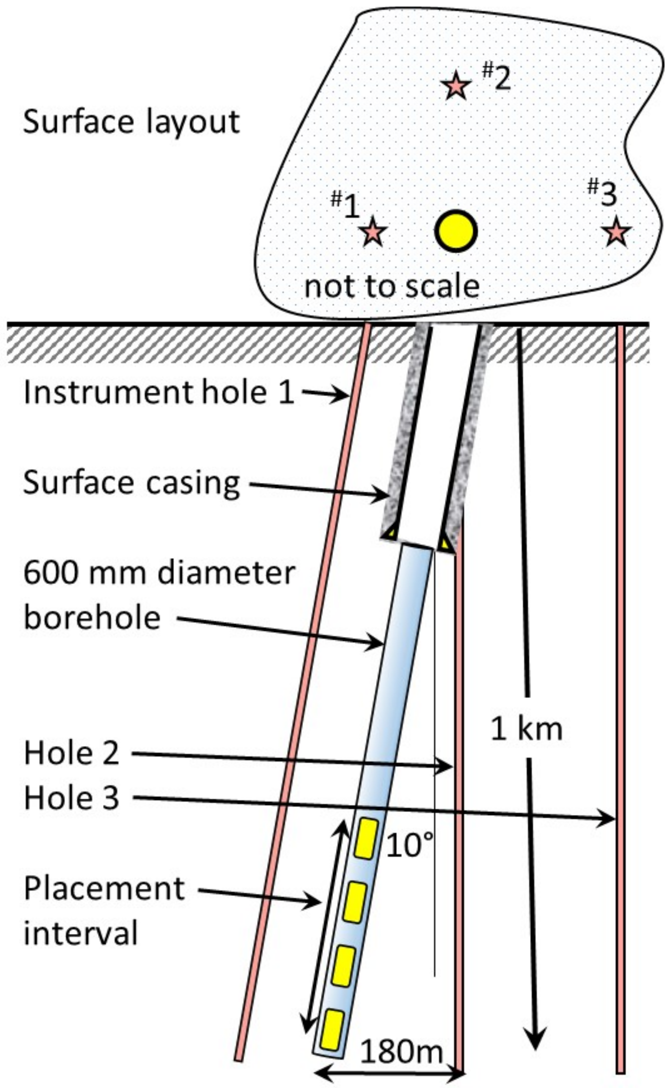


*Figure I-11: The basic plan and cross-section views of the proposed demonstration site*

## Appendix II: Cost of Deep Borehole Placement - Literature Review and Model Development

### Introduction

This appendix outlines the literature that the cost estimate and associated Excel models are based on. We provide an overview of the relevant work completed in the selected sources, and the contributions that these sources make to the cost analysis development.

In light of the uncertainties associated with the final design, implementation and operation of a project for deep borehole placement of solid radioactive wastes, the cost estimates and analyses presented here are but general guides to final costs. Among many other sources of uncertainty, and focussing only on the aspects relating to boreholes, we note that costs are substantially sensitive to the following factors:

- Borehole depth and diameter
- Lengths of cemented casing (and the possibility of exotic casings)
- Special cement formulations for the casings
- Spacing of canisters within boreholes
- Minimum depth of high level waste canisters (how much of the hole is used)
- Design, manufacture and placement of the buffer material for high level waste canisters
- Placement design for intermediate and low level radioactive wastes (e.g. same wellbores as high-level wastes but in the upper part? Or dedicated wellbores?)

These decisions can only be made in the context of an actual engineering design framework (FEED – front-end engineering design), informed by scientific and site characterization data and many of them will remain significantly uncertain even in the early construction stages.

The major and perhaps most relevant sources for the cost analysis are published by Sandia National Laboratories (SNL) in the United States. SNL has been contracted by the Department of Energy (DOE) in the US to complete the development and review of various programs for geothermal drilling, and nuclear waste storage programs. On the topic of nuclear waste storage, SNL was involved in a DOE project to evaluate the possibility of deep borehole disposal (DBD) with the Deep Borehole Field Test (DBFT) project. This project was defunded by the DOE in 2017 prior to any field testing being completed; however, SNL has continued to invest resources in DBD and has prepared many reports on the DBFT and general safety cases for DBD. Additionally, SNL has developed multiple presentations for various national and international organizations pertaining to conducting DBFT-like projects.

The costing scheme developed herein is primarily from SNL sources initially stemming from an economic analysis of drilling a 5 km deep well for an Enhanced Geothermal Systems (EGS) in the US. The various values reported in this EGS well cost analysis have been modified by SNL based on the considerations that may arise in a DBD program for solid radioactive wastes. SNL, in various technical presentations to different national organizations, presents further costing assessments for different aspects of a standard DBD project; these presentations are provided here. However, limited information is provided in the SNL literature and presentations about how the specific costing inputs were chosen.

In addition to the SNL costing, some individuals have attempted to generate costing for DBD or aspects of it. A PhD thesis by Bates (2015) contains modeling data in an effort to determine the most cost-effective depth for deep borehole storage. Bates (2015) developed costing for all aspects of the disposal to develop an optimization script. This paper relied on costing data from different sources to develop values to populate his formulas. A more detailed description of this paper is presented below.

**Literature Summary**

In this section an overview of selected sources is provided and important data from those articles are documented. The sources are ordered based on publication date to demonstrate how the various sources build off each other. The first group of sources is produced by SNL.

Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report (Polsky *et al*., 2008)

SNL undertook a technology evaluation program for enhanced geothermal system (EGS) development looking at areas to reduce costs associated with the construction and operation of geothermal wells. A significant portion of this review involved a "drilling on paper" exercise where the authors contracted a geothermal drilling contractor to cost a step-by-step drilling program for a 6 km deep geothermal well. Figure II-1 shows a schematic of the well design used to complete the analysis.

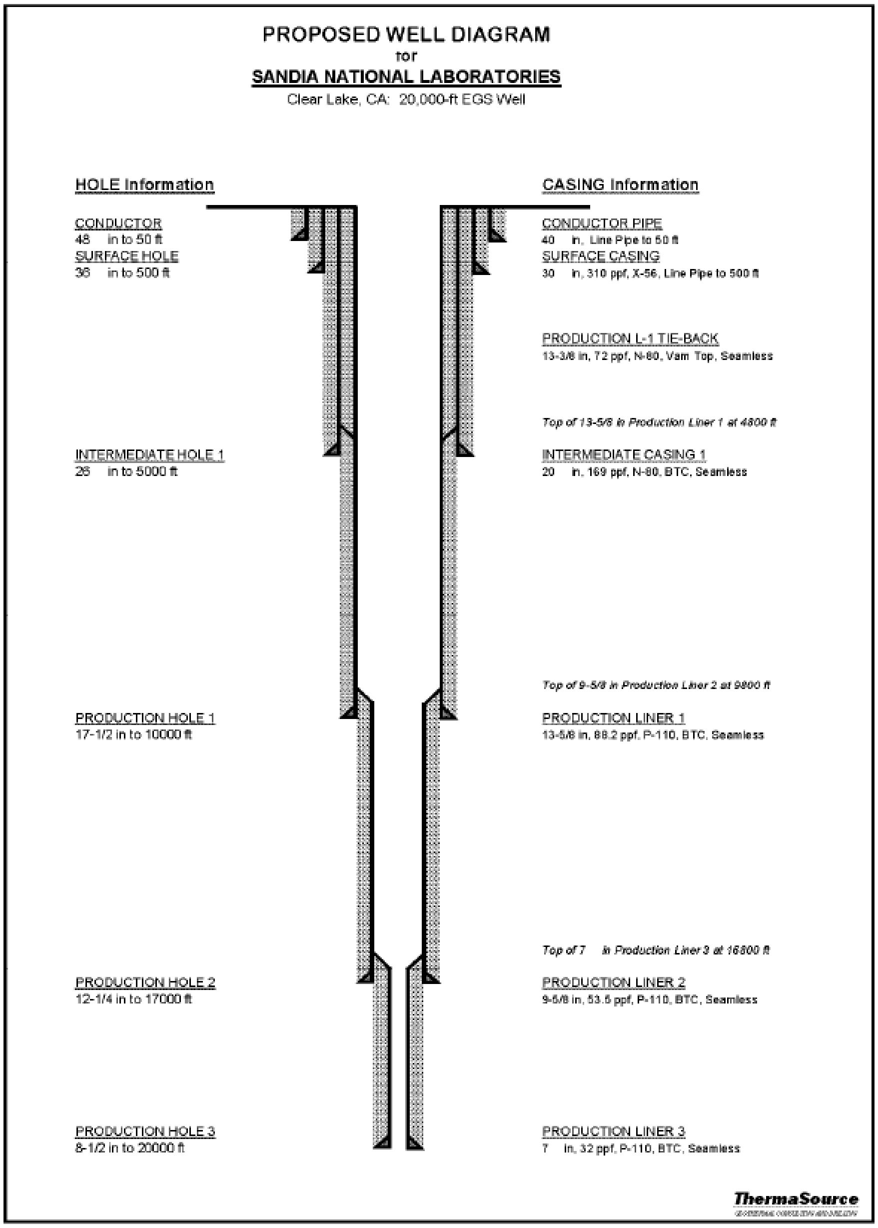


*Figure II-12: Schematic of EGS Well (Polsky et al., 2008)*

The drilling program was estimated to cost $21 million USD in 2008 with $16 million associated with equipment rental and services and $5 million associated with materials and consumable services. In addition to the costing of the step-by-step process, the time associated with every step of the project was also tabulated with an estimated duration of 142 days. Figures II-2 through 4 highlight various aspects of the costing and time estimates. More granular costing and time estimates for the work completed are available in the source report.

**SUMMARY OF ESTIMATED COSTS**

| | | |
|---|---|---|
| EQUIPMENT RENTAL AND SERVICES | $ | 15,810,000 |
| MATERIALS, CONSUMABLES AND RELATED SERVICES | $ | 5,530,000 |
| TOTAL DRILLING COST | $ | 21,340,000 |

| Code | COST CATEGORIES | Total Cost |
|---|---|---|
| | EQUIPMENT RENTAL AND SERVICES | $ 15,810,000 |
| 10 | RIG MOBILIZATION and DEMOBILIZATION | - |
| 20 | CONTRACT DRILLING RIG | 6,230,000 |
| 30 | PLANNING, ENGINEERING AND PROJECT MANAGEMENT | 750,000 |
| 40 | DRILLING FLUIDS AND SOLIDS CONTROL | 1,060,000 |
| 50 | DIRECTIONAL DRILLING SERVICES | 1,400,000 |
| 60 | CEMENT and SERVICES | 3,680,000 |
| 70 | AIR DRILLING SERVICES | 530,000 |
| 80 | GEOLOGIC EVALUATION AND RESERVOIR ENGINEERING | 1,080,000 |
| 90 | DRILLING TOOLS RENTAL AND REPAIR | 480,000 |
| 100 | WELL CONTROL EQUIPMENT RENTAL AND SERVICES | 320,000 |
| 110 | RIG SITE LOGISTICS | 170,000 |
| 120 | ROAD AND LOCATION CONSTRUCTION | - |
| 130 | TRUCKING AND TRANSPORTATION | 110,000 |
| 140 | COMPLETION SERVICES | - |
| 150 | FISHING TOOLS AND SERVICES | - |
| | MATERIALS, CONSUMABLES AND RELATED SERVICES | $ 5,530,000 |
| 160 | BITS | 790,000 |
| 170 | CASING AND TUBING | 4,370,000 |
| 180 | CASING ACCESSORIES | 190,000 |
| 190 | PRODUCTION EQUIPMENT | 180,000 |
| 200 | NEW CATEGORY | - |

*Figure II-13: Overview of Cost Breakdown (Polsky et al., 2008)*

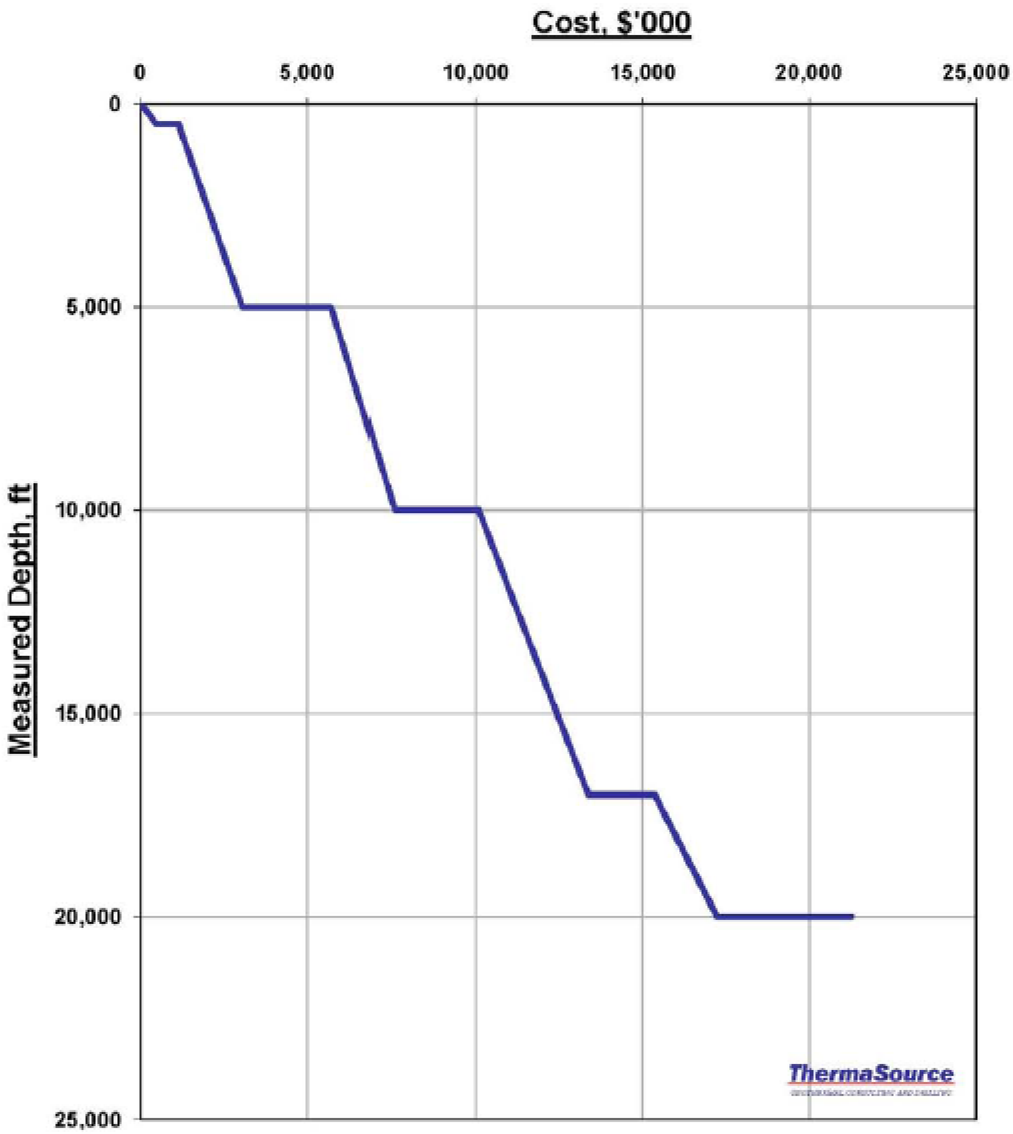


*Figure II-14: Cost vs. Depth for EGS Well (Polsky et al., 2008)*

| Task Code | 1 Surface | 2 INT-1 | 3 PROD-1 | 4 PROD-2 | 5 PROD-3 | 6 PL1-TB | General | Grand Total |
|---|---|---|---|---|---|---|---|---|
| BHA | $148,916 | $153,840 | $291,501 | $252,146 | $264,786 | $213,468 | | $1,324,657 |
| BOP | $81,620 | $62,785 | $0 | $0 | $0 | $81,620 | | $226,024 |
| Casing | $170,000 | $950,000 | $1,123,200 | $705,600 | $217,600 | $1,128,000 | | $4,294,400 |
| Casing Consumables | | | | | | | $255,000 | $255,000 |
| Cement | $258,171 | $1,258,078 | $758,349 | $577,114 | $368,342 | $690,428 | | $3,910,481 |
| Circ | $6,278 | $14,116 | $34,045 | $132,817 | $155,906 | $12,557 | | $355,720 |
| Drill | $109,728 | $987,550 | $909,173 | $1,786,996 | $852,750 | $6,278 | | $4,652,477 |
| Drilling Consumables | $193,155 | $582,450 | $354,380 | $352,590 | $185,492 | | | $1,668,067 |
| Log | $130,813 | $165,691 | $200,569 | $241,261 | $270,326 | | | $1,008,660 |
| RigU/D | $24,183 | $12,557 | $12,557 | $6,278 | $6,278 | $6,278 | | $68,132 |
| RunCsng | $31,392 | $94,177 | $94,177 | $125,569 | $125,569 | $43,949 | | $514,834 |
| Trip | $36,070 | $203,561 | $309,909 | $768,065 | $833,203 | $100,455 | | $2,251,263 |
| WH Ops | $43,949 | $75,341 | | | | $69,063 | | $188,354 |
| Grand Total | $1,234,276 | $4,560,146 | $4,087,861 | $4,948,436 | $3,280,253 | $2,352,097 | $255,000 | $20,718,069 |
| Cost/ft | $2,469 | $1,013 | $818 | $707 | $1,093 | | | |

**Table 5-5 Task cost pivot table by interval including interval cost per foot**

| | 1 Surface | 2 INT-1 | 3 PROD-1 | 4 PROD-2 | 5 PROD-3 |
|---|---|---|---|---|---|
| BHA | $298 | $34 | $58 | $36 | $88 |
| BOP | $163 | $14 | $0 | $0 | $0 |
| Casing | $340 | $211 | $225 | $101 | $73 |
| Casing Consumables | $0 | $0 | $0 | $0 | $0 |
| Cement | $516 | $280 | $152 | $82 | $123 |
| Circ | $13 | $3 | $7 | $19 | $52 |
| Drill | $219 | $219 | $182 | $255 | $284 |
| Drilling Consumables | $386 | $129 | $71 | $50 | $62 |
| Log | $262 | $37 | $40 | $34 | $90 |
| RigU/D | $48 | $3 | $3 | $1 | $2 |
| RunCsng | $63 | $21 | $19 | $18 | $42 |
| Trip | $72 | $45 | $62 | $110 | $278 |
| WH Ops | $88 | $17 | $0 | $0 | $0 |
| Grand Total | $2,469 | $1,013 | $818 | $707 | $1,093 |

**Figure 5-8 Task cost per foot**

*Figure II-15: Cost of Different Drilling Activities at Different Construction Phases (Polsky et al., 2008)*

<u>Deep Borehole Disposal of High-Level Radioactive Waste (Brady *et al.*, 2009)</u>

This paper presented the first cost estimate for deep borehole disposal from the SNL research group. The report simply pointed to the work completed by Polsky *et al*. (2008) as a reasonable enough analog for deep borehole disposal drilling to make a comparison. The design was modified slightly with a final depth of 5 km as opposed to 6 km and with some modifications to the borehole dimensions. The report estimated that the novel borehole design would be approximately $20 million USD and be able to be constructed in 110 days. Figure II-5 shows the reference design utilized for the DBD.

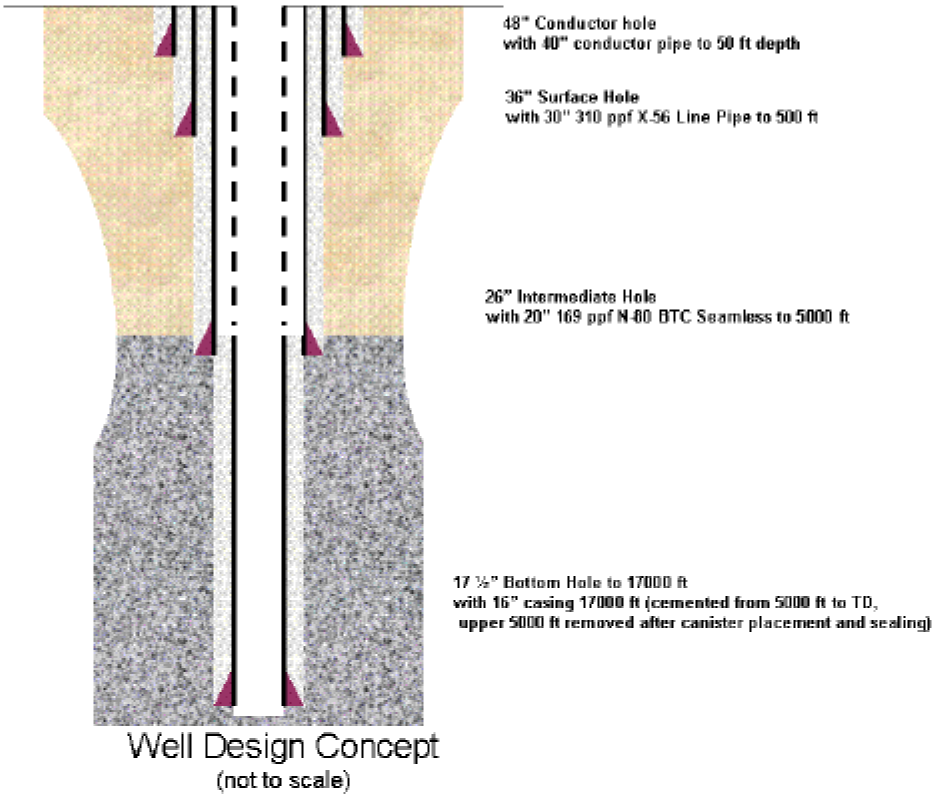


*Figure II-16: DBD Conceptual Design (Brady et al., 2009)*

<u>Deep Borehole Disposal of Nuclear Waste: Final Report (Arnold *et al*., 2011)</u>

Expanding on the relatively simple analysis and results presented in Brady *et al*. (2009), the 2011 report provided costing for more aspects of the deep borehole including waste canister loading, emplacement and long-term sealing. The costing is also completed for three different drilling scenarios. Scenario A is the costing associated with drilling the initial exploratory borehole. Scenario B is the costing associated with drilling the functional storage borehole with a pre-drilled small diameter borehole to evaluate the lithology and conduct sampling and subsurface characterization measurements (flow testing, geophysical logging…). Scenario C is the cost of drilling the functional storage borehole with limited coring and downhole testing prior to emplacement. Figure II-6 shows the costs of each scenario and the estimated days to complete it.

**Table 5. Estimated Drilling, Casing and Completion Costs**

| HOLE DESIGN | A | B | C |
|---|---|---|---|
| **Interval costs** | | | |
| Drilling time cost | $3,906,016 | $7,421,582 | $4,882,520 |
| Tripping time cost | $2,446,664 | $5,905,986 | $3,058,330 |
| Bit cost | $631,322 | $3,861,709 | $1,753,587 |
| Other BHA | $315,661 | $1,930,855 | $876,793 |
| Mud cost | $582,970 | $1,732,607 | $987,607 |
| Casing cost | $1,183,200 | $4,777,425 | $4,777,425 |
| Cementing time cost | $372,500 | $790,625 | $790,625 |
| Cementing mat'l cost | $1,356,829 | $2,339,904 | $2,339,904 |
| Trouble time | $0 | $0 | $0 |
| Trouble cost | $0 | $0 | $0 |
| Directional drilling | $467,850 | $1,475,040 | $951,165 |
| Logging time | $645,000 | $806,250 | $806,250 |
| Logging service | $200,000 | $200,000 | $200,000 |
| Wellhead time | $120,000 | $225,000 | $225,000 |
| Other costs | $1,612,500 | $2,015,625 | $0 |
| **Total interval costs** | **$13,840,512** | **$33,482,609** | **$21,649,206** |
| | | | |
| **Additional costs and time** | | | |
| Mobilization/De-mob | $800,000 | $1,000,000 | $1,000,000 |
| Site prep, cellar, conductor | $100,000 | $100,000 | $100,000 |
| Pre-spud engineering | $300,000 | $300,000 | $300,000 |
| Casing hangers, port collar, packers | $300,000 | $500,000 | $500,000 |
| Wellhead equipment | $300,000 | $500,000 | $500,000 |
| Contingency (15%) | $1,920,748 | $5,022,391 | $3,247,381 |
| **Total well cost** | **$17,561260** | **$40,905,000** | **$27,296,587** |
| **Total project time, days** | **160.7** | **211.0** | **139.2** |

Note: All costs are in 2011 $US and approximately for 2011 expenses.

*Figure II-17: Cost Estimates for Different Drilling Scenarios (Arnold et al., 2011)*

Costing tables were provided for the newly considered items associated with the project (Figures II-7 through II-9). The estimated waste canister and loading costs are dominated by the costs associated with the construction and placing of the waste in the canisters and sealing them before placement in the boreholes. The estimates for waste emplacement assumed that it would take 10 trips to place all 400 canisters downhole with associated plugs. Borehole sealing estimates assumed that bentonite plugs would be placed by wireline in 5 m segments and that cement plugs would be emplaced through a drill pipe directly onto the uppermost canister.

| | Cost per Waste Canister | Cost per Borehole |
|---|---|---|
| Waste Canister Materials | $7,750 | $3,100,000 |
| Thread Cutting | $1,000 | $400,000 |
| Tenaris Blue Connection | $500 | $200,000 |
| Fuel Assembly Dismantlement and Canister Loading | $7,824 | $3,129,600 |
| Canister Welding | $1000 | $400,000 |
| Weld Inspection | $1000 | $400,000 |
| **Total** | | **$7,629,600** |

Note: All costs are in 2011 $US and approximately for 2011 expenses.

*Figure II-18: Estimated Waste Canister and Loading Costs (Arnold et al., 2011)*

| | Rig Time (hours) | Cost per Borehole |
|---|---|---|
| Surface Handling and Canister String Assembly | 200 | $625,000 |
| J-Slot Assembly | - | $135,000 |
| Canister String Emplacement | 240 | $750,000 |
| Setting Bridge Plugs | 60 | $187,500 |
| Cement Plugs Emplacement | 300 | $937,500 |
| Bridge Plugs and Cement | - | $140,000 |
| **Total** | 800 | **$2,775,000** |

Note: All costs are in 2011 $US and approximately for 2011 expenses.

*Figure II-19: Estimated Waste Canister Emplacement Costs (Arnold et al., 2011)*

**Table 8. Estimated Borehole Sealing Costs**

| | Rig Time (hours) | Cost per Borehole |
|---|---|---|
| **Lower Uncased Sealing and Plugging Zone** | | |
| Cutting and Pulling Casing | 20 | $62,500 |
| Cement Plugs Emplacement | 146 | $455,000 |
| Cement Plugs Materials | | $768,000 |
| Bentonite Seals Emplacement | 57 | $177,083 |
| Bentonite Seals Materials | | $46,700 |
| Backfill Emplacement | 20 | $62,500 |
| Backfill Materials | | $7,800 |
| **Upper Cased Sealing and Plugging Zone** | | |
| Bridge Plugs Emplacement | 8.5 | $26,563 |
| Cement Plugs Emplacement | 44 | $137,500 |
| Cement Plugs Materials | | $630,000 |
| Backfill Emplacement | 20 | $62,500 |
| Backfill Materials | | $14,000 |
| **Total** | | **$2,450,146** |

Note: All costs are in 2011 $US and approximately for 2011 expenses.

*Figure II-20: Estimated Borehole Sealing Costs (Arnold et al., 2011)*

The authors decided that the likely path forward was using scenario C with limited logging and no pilot bore. The significant changes from Brady *et al*. (2009) to Arnold *et al*. (2011), besides the addition of new components, was the increase in drilling cost from $20 million to $27 million (Figure II-10). This is due to new requirements for logging and testing, along with a contingency of 15%.

| | Cost per Borehole |
|---|---|
| Drilling, Casing, and Borehole Completion | $27,296,587 |
| Waste Canisters and Loading | $7,629,600 |
| Waste Canister Emplacement | $2,775,000 |
| Borehole Sealing | $2,450,146 |
| **Total** | **$40,151,333** |

Note: All costs are in 2011 $US and approximately for 2011 expenses.

*Figure II-21: Estimated Systems Costs*

<u>Deep Borehole Field Test Conceptual Design Report (Hardin, 2016)</u>

As part of the SNL conceptual design for the DBFT, a comparison of emplacement methods was undertaken. A cost-risk analysis of wireline and drill string methods of emplacement for the waste canisters was conducted and included in their reports. SNL stated preference for the wireline emplacement method, resulting in an estimated cost of $24 million USD compared to the $42 million USD cost of the drill string method, although it was estimated that it would take approximately 430 days for both based on the probability of "off-normal" events occurring. Figure II-11 presents a breakdown of the costing associated with two waste emplacement methods

Table C-1. Cost estimate breakdown for waste package emplacement options

| **Waste Package Emplacement Cost Estimates** | | |
|---|---|---|
| | | |
| Number of waste packages | 400 | |
| Project duration | 430 | days |
| Number of intermediate plugs | 10 | |
| **Drill-String Option** | | |
| **Time-Dependent Costs** | **Daily Rate** | **Subtotal** |
| Drill rig (workover) | $ 75,000 | $ 32,250,000 |
| Crane | $ 6,000 | $ 2,580,000 |
| Iron roughneck | $ 3,000 | $ 1,290,000 |
| Power tongs | $ 1,000 | $ 430,000 |
| Power slips | $ 3,000 | $ 1,290,000 |
| BOP stack | $ 2,500 | $ 1,075,000 |
| Subtotal | | $ 38,915,000 |
| **Intermediate plugging costs** | **Each** | **Subtotal** |
| Bridge plugs | $ 20,000 | $ 200,000 |
| Cementing | $ 40,000 | $ 400,000 |
| Wireline cementing surveys | $ 80,000 | $ 800,000 |
| Subtotal | | $ 1,400,000 |
| **One-Time Costs** | | |
| Build pad and basement | | $ 500,000 |
| Build structural frame | | $ 100,000 |
| Build transfer track system | | $ 1,000,000 |
| Subtotal | | $ 1,600,000 |
| **Total Drill-String Emplacement Project Cost** | | **$ 41,915,000** |
| | | |
| **Wireline Option** | | |
| **Time-Dependent Costs** | **Daily Rate** | **Subtotal** |
| Wireline unit | $ 37,000 | $ 15,910,000 |
| Crane | $ 6,000 | $ 2,580,000 |
| BOP stack | $ 2,500 | $ 1,075,000 |
| Subtotal | | $ 19,565,000 |
| **Intermediate plugging costs** | **Each** | **Subtotal** |
| Bridge Plug | $ 20,000 | $ 200,000 |
| Coiled-tubing unit and cementing | $ 200,000 | $ 2,000,000 |
| Wireline cementing surveys | $ 80,000 | $ 800,000 |
| Subtotal | | $ 3,000,000 |
| **One-Time Costs** | | |
| Build headframe | | $ 500,000 |
| Build pad and control room | | $ 350,000 |
| Build radiation shield enclosure | | $ 100,000 |
| Subtotal | | $ 950,000 |
| **Total Wireline Emplacement Project Cost** | | **$ 23,515,000** |

*Figure II-22: Cost Estimate Breakdown for Waste Package Emplacement Options*

This estimate updates the one developed in Arnold *et al*. (2011) where it was assumed that the waste canister emplacement would cost ~$2.8 million USD.

Deep Borehole Disposal in Israel (Mackinnon *et al*., 2018)

This presentation is the most up-to-date costing that currently is available. The presentation was a part of a series of technical presentation developed by SNL summarizing the work completed by the DBFT team. This presentation was developed for Israeli agencies looking at storage for their nuclear waste.

The presentation provides pricing for a single borehole disposal unit (~$ 100M USD), and a group of five boreholes (~$315M USD). In a change from prior cost estimates, the cost of siting is included. The breakdown of the different line items titles is different from previous cost estimates, but it is obvious enough to see the continuity from other reports. Figure II-12 provides a breakdown of the cost estimates associated with the project.

| DBD Cost Item | Single Deep Borehole Item ($10^6$$ per borehole) | Total DBD Cost (5 boreholes) ($10^6$$) |
|---|---|---|
| Siting | 45 | 45 |
| Construction | 20 | 100 |
| Operation | 20 | 100 |
| Closure | 5 | 20 |
| Encapsulation | 10 | 50 |
| **TOTAL (2017 $10^6$$)** | **100** | **315** |

*Figure II-23: DBD Cost Breakdown (Mackinnon et al., 2018)*

In addition to the cost estimates associated with the construction of a useable facility, the presentation provides a cost breakdown for completion of a feasibility study with a similar scope to the DBFT. This cost is broken down over six years; the estimated time required to complete the project. The total cost is estimated to be $96M USD (Figure II-13)

| Work Scope Element | FY1 | FY2 | FY3 | FY4 | FY5 | FY6 | Total |
|---|---|---|---|---|---|---|---|
| Site Evaluation | 1.9 | 2.4 | 1.2 | | | | 5.5 |
| Characterization Borehole (0.22 m BHD) (Site Management, Design, Drilling, and Testing) | 1.2 | 16.0 | 13.8 | 2.8 | | | 33.8 |
| Deep Borehole Disposal System Analysis (Post Closure) | 0.3 | 0.4 | 0.4 | 0.5 | | | 1.6 |
| Project Management | 0.40 | 1.2 | 1.2 | 0.6 | | | 3.4 |
| Field Test Borehole (0.43 m BHD) (Site Management, Design, and Drilling) | 0.4 | 0.3 | 3.3 | 13.5 | 13.2 | 0.7 | 31.4 |
| Emplacement System (Design, Packaging, Emplacement System Components, and Demonstration) | 1.9 | 1.2 | 1.9 | 3.3 | 4.4 | 2.5 | 15.2 |
| Deep Borehole Disposal System Analysis (Pre-Closure) | | | | | 1.0 | 1.0 | 2.0 |
| Project Management | | | | 0.6 | 1.2 | 1.2 | 3.0 |
| Total | 6.1 | 21.5 | 21.8 | 21.3 | 19.3 | 4.9 | 95.9 |

*Figure II-24: Breakdown of DBFT-like Project (Mackinnon et al., 2018)*

The presentation does not make a case or present any information about how the cost of first completing a field test prior to the construction of a functional storage facility would result in cost savings. It is evident that some of the costs for the field test and the construction of a functioning storage facility are one-to-one (such as the field test borehole line $31.4M USD in 2017 compared to ~$27M USD Brady *et al*. (2012)), whereas some are not (estimated testing of emplacement is $15M USD compared to Hardin's (2016) estimate of $24M USD). It is evident that there would be some additional cost moving from a field test to the constructed repository, but if the regulator allowed for the test borehole to be used for storage, there is significant potential for cost savings.

<u>Optimization of Deep Borehole for Disposal of High Level Nuclear Waste (Bates, 2015)</u>

Bates' (2015) PhD thesis set out to optimize the disposal of nuclear waste in deep boreholes. Instead of developing a group of fixed costs for a specific reference design as the SNL research group had done, Bates developed an optimization script involving fixed and variable costs depending on depth and spacing of the borehole array to determine the optimal borehole length. The model developed produced results with the final depth of boreholes being approximately 2500 m. A limiting factor seem to be that the additional costs of drilling deeper holes and total emplacement time tends to result in the model preferring many shallower boreholes for storage.

In order to conduct this analysis Bates developed formulas to estimate the costs associated with drilling, site characterization and emplacing canisters. The values used to populate these formulas are obtained from a variety of different sources. A full look into the methodology is provided in Chapter 5 of Bates' (2015) thesis. Pertinent summary tables are provided in Figures II-14 and II-15.

**Table 5-8.** Description and equations for the cost models used in the DBD design trade study.

| **Description** | | **Equation** | **Variable definitions** |
|---|---|---|---|
| Costs per unit kilogram of SNF disposed | Unit costs (UC) | $M_{tot} = L_d \rho_l$<br>$UC_{tot} = M_{tot}(UC)$ | $L_d$: Disposal zone length (m)<br>$\rho_l$: Linear density of SNF (100 kgHM/m)<br>$UC$: <$65/kgHM |
| Drilling cost vs. total depth | Drilling costs (DC) | $DC = DC_0 e^{\lambda_d(L_d+L_p)}$ | $DC_0$: Fixed cost ($10M)<br>$\lambda_d$: Cost constant (1/m)<br>$L_p$: Plug length (m) |
| Costs for characterizing an area of land | Site char. (SC) | $SC = C_a A$<br>$A = 2P^2$ | $C_a$:Cost/area of site characterization ($/m$^2$)<br>$A$: Area of single borehole<br>$P$: Borehole spacing |
| Cost for emplacing all canisters | (EC) | $EC_l L_{d,avg}\left(\frac{L_d}{L_{can}}\right)$ | $EC_l$: Per canister emplacement costs ($/(km-can))<br>$L_{can}$: Canister length (5 m)<br>$L_{d,avg}$: ($L_p$+0.5 $L_d$) |

*Figure II-25: Equations for Cost Models for DBD Design (Bates, 2015)*

**Table 5-9.** Summary of lower bound, middle, and upper bound cost parameters.

| **Cost type** | **Lower Bound** | **Middle Estimate** | **Upper Bound** |
|---|---|---|---|
| DC | $\lambda_d$= 0.666 km$^{-1}$ | $\lambda_d$= 0.94 km$^{-1}$ | $\lambda_d$=1.051 km$^{-1}$ |
| SC | $C_a$=$1.25/m$^2$ | | $C_a$ =$22/m$^2$ |
| EC | $EC_l$=$539/(canister-km) | | $EC_l$=$15,919/(canister-km) |

*Figure II-26: Equation Inputs for Cost Model (Bates et al., 2015)*

The model developed demonstrates clearly the effects of increasing depth of boreholes on overall cost of the project. The functionality between cost and depth, other factors held constant, is well-know to be strongly non-linear, and the choice of exponent in the drilling costs equation allows this to be assessed. However, with the set of formulas used, his model does not easily allow for the input of various fixed costs. This appears to be deliberate, as the analysis was intended to develop an optimization approach based on several linear and non-linear functions, without accounting for a list of fixed costs. To carry out a more complete costing analysis would involve identifying a wider list of cost items and stipulating which are fixed (constant), which are linear functions with other variables (such as number of holes), and which are non-linear. If an approach like this is followed, it requires supplementing the marginal costs with additional fix costing.

Further to this, using an approach such as this relies on a detailed understanding of the underlying inputs into the formula variables, as the functionalities are not always obvious, nor are they easily available from a competitive industry such as drilling. Specifically, in Bates' (2015) work, costing associated with site characterization was probably significantly underestimated, and should be updated for a repository cost assessment. For costing associated with drilling, the exponential factors would require confirmation of the suitability for the specific drilling program prescribed. Figure II-16 shows significant variability in estimates of drilling costs and the basis for the rank of exponential factors.

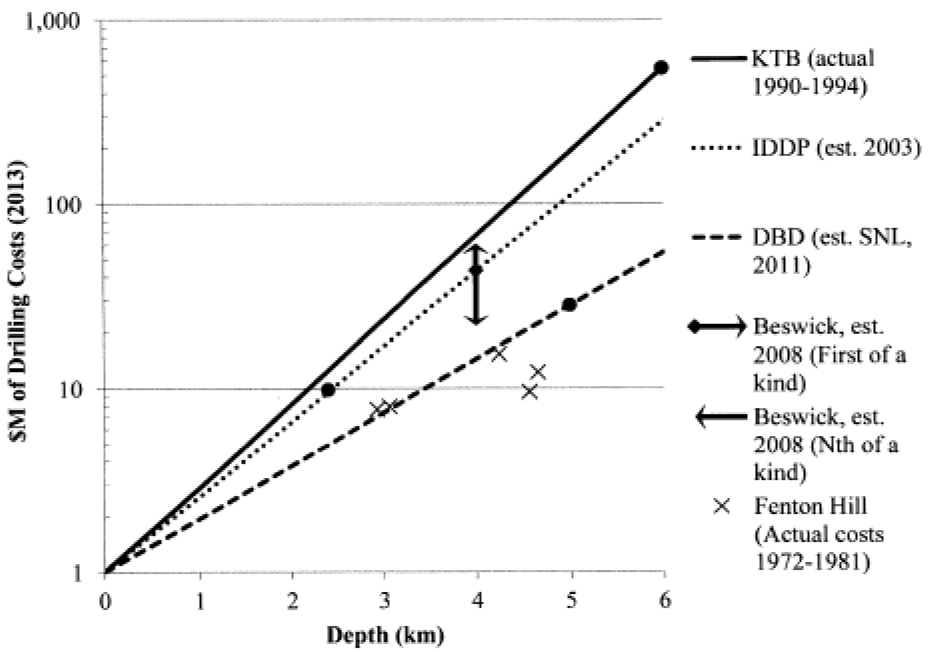


**Figure 5-5.** Comparison of drilling costs vs. depth based on various actual and estimated costs for deep boreholes. All costs are adjusted to 2013.

*Figure II-27: Comparison of Drilling Cost and Depth (Bates, 2015)*

<u>Summary of Literature Review</u>

One clear conclusion from the analyses reviewed is the major impact of drill rig time. The operating cost of a drill rig is several times greater than the operating cost of a high-quality wire-line placement system. Because of the large CAPEX involved in a drilling rig, there is an incentive to use it continuously (continuous shifts), and to minimize idle time that might be associated with canister placement and buffer material installation. Furthermore, it is not clear that wireline placement is inherently safer or less safe than placement with the drill rig, so risk analysis (involving the escape of radionuclides or personnel injury from industrial accidents) would not point strongly to one or another technique.

The data that has been examined is limited and is focused on deep boreholes and conventional oil and gas drilling technologies. We believe that there are better approaches that do not substantially increase risk, and are almost certainly more economical.

**<u>Costed Drilling Program</u>**

Developing a costed model for the entire development process is not practical in the context of this report. Too many unknowns exist for the authors to provide an estimate for a specific scenario. However, the costing presented in the literature summary presented above is a good basis for tailoring expectations of future programs.

A costed drilling program model was developed using the experience of the authors in drilling program development in different industries. This model provides an order of magnitude estimate for the overall project cost, with key geometric and cost items configurable to arrive at a total cost for the drilling portion of the project.

The following sections will discuss model assumptions, the inputs for the costed model, the cost of a base case scenario for a 1 km deep borehole, and the results of a sensitivity analysis undertaken to evaluate the program costs compared to a base case.

Model Assumptions

*Two Phases of Drilling:*

The model allows for costing of a two-phase drilling program. The first phase of this drilling program is assumed to be the advancement of a small diameter pilot hole with potential for downhole testing and instrumentation during this phase. The second phase consists of the drilling activities to construct and finalize the large diameter repository borehole. These two phases will be completed by different drilling equipment.

*Three Borehole Sections:*

The repository borehole is assumed to have three unique sections with different diameters. Each of these sections in the model is described by the type of casing (or lack there of) that will be placed in this section. The sections are:

- Conductor Casing (top and largest diameter section with very short depth)
- Surface Casing (middle section extending from conductor casing section to top of repository section)
- Repository Section (bottom and smallest diameter section)

*Different Drilling Method for Conductor Section:*

It is assumed that the conductor section will be drilled by a smaller truck mounted rig than the larger deeper drilling rig that will be employed to advance the borehole until termination of the repository section. Because of this, the costing estimate for this section is provided as a lump sum for all components (casing, drilling, etc.) as it is expected to take a much shorter period of time to complete (1-day). The other sections will be costed using daily rates for drill equipment, and per-meter costs for materials such as casing.

*Multiple Boreholes with Same Parameters:*

The drilling cost model assumes that all boreholes constructed will have the same dimensions, geometries, and in turn have the same cost to construct. The user does not need to input the number of boreholes required, the model calculates the number of boreholes by determining the requirements for storage using the length available for storage and the length of waste and buffer material required to be stored.

<u>Model Inputs</u>

A generic borehole with labelled sections that allow for input of dimensioned geometric parameters is shown in Figure II-17. The labels correspond with inputs in the EXCEL model. Figure II-18 shows the colour legend for user inputs and calculated values in the model.

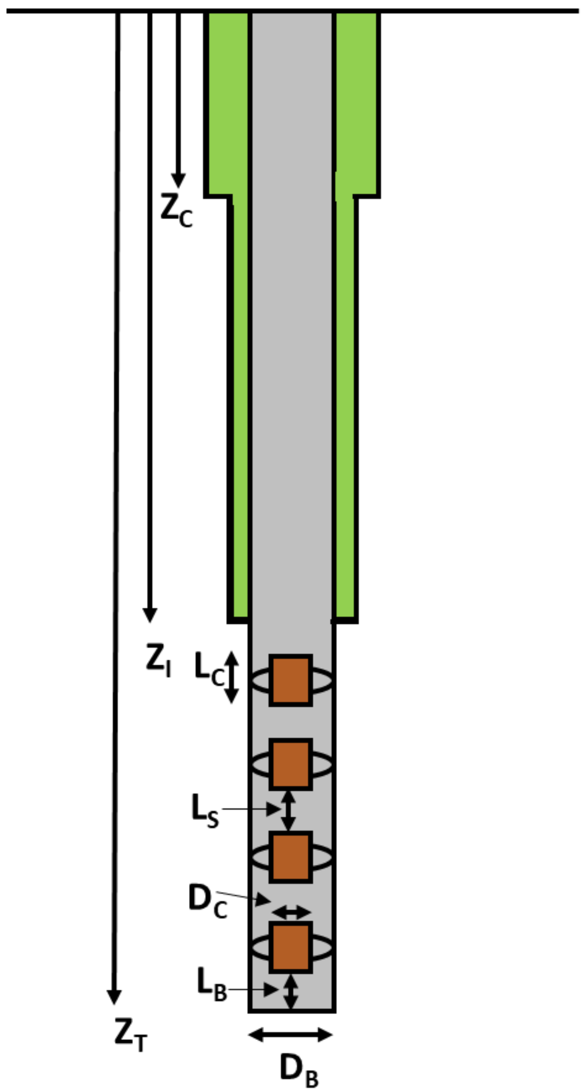


*Figure 28: Generic Repository with Labelled Dimensions*

| | |
|---|---|
| **Legend** | |
| **Inputted Values** | |
| **Computed Values** | |

*Figure II-29: Model Input Legend*

Figure II-19 shows the inputs for the borehole geometry. There are four inputs for the borehole sections. The top three inputs are for the depth of the various sections of the borehole (conductor, surface, and repository section). The fourth input is the top depth for the emplacement of waste. The model allows for emplacement of waste up to a certain height in the borehole. If there is more waste than that can be stored in a borehole, the model will add additional boreholes (of the same dimensions).

| **Borehole Sections** | |
|---|---|
| Depth of Conductor Casing (m) Zc | 20 |
| Depth of Surface Casing (m) Zt | 300 |
| Depth of Repository Section (m) Zt | 1000 |
| Top Emplacement Depth (m) | 700 |

*Figure II-30: Borehole Section Inputs*

Figure II-20 shows the inputs available for borehole and casing diameters. These inputs do not directly affect the cost outputs of the model, but, can be used to estimate the requirements for cementing (Figure II-21).

| **Borehole Diameter** | |
|---|---|
| Conductor Section (m) | 0.85 |
| Surface Section (m) | 0.75 |
| Repository Section (m) | 0.6 |
| **Casing Diameter** | |
| Conductor Section OD (m) | 0.81 |
| Conductor Section ID (m) | 0.78 |
| Surface Section OD (m) | 0.66 |
| Conductor Section ID (m) | 0.63 |
| Repository Section OD (m) | N/A |
| Repository Section ID (m) | N/A |

*Figure II-31: Borehole and Canister Diameter Inputs*

| **Cement Volumes** | |
|---|---|
| Conductor Section (m^3) | 1.0 |
| Surface Section (m^3) | 27.9 |
| Repository Section (m) | N/A |

*Figure II-32: Cement Volumes Calculated*

Figure II-22 shows the model inputs for the waste and canister inventory, the buffer geometry, and the borehole inventory. The waste is inputted as a mass of total waste and a total mass of waste per canister. Using this, the total number of canisters can be calculated. The canisters are then assigned a length and a diameter (diameter input has no bearing on cost, however, should be less then ID of repository section). Buffer material geometric inputs allow for input of buffer material between each canister and at the bottom of the borehole. Using all of these geometric inputs, the total length is determined, and the number of boreholes is calculated and rounded up to the nearest integer.

| | |
|---|---|
| **Waste Inventory** | |
| Quantity of Waste (kg) | 16500 |
| Quantity of Waster per Cannister (kg) | 200 |
| **Cannister Inventory** | |
| Number of Cannisters | 83 |
| Length of Cannister (m) [Lc] | 2 |
| Diameter of Cannister (m) [Dc] | 0.4 |
| **Buffer Geometry** | |
| Spacing Between Cannister (m) [Ls] | 1 |
| Cushion at Bottom of Emplacement Zone (m) [Lb] | 5 |
| **Borehole Inventory** | |
| Fraction of Emplacement Zone Filled | 0.85 |
| Number of Boreholes Required | 1 |

*Figure II-33: Waste and Canister Inventory, Buffer Geometry, and Borehole Inventory Inputs*

Cost inputs are broken down in different sections. The first section is the pilot hole costs (Figure 23). The model uses lump sum inputs for both the pilot hole construction and any required testing program at this phase of drilling.

| | |
|---|---|
| **Pilot Hole Construction** | |
| Construction Cost ($) | $ 200,000 |
| Testing Program ($) | $ 150,000 |
| Pilot Hole Cost ($) | $ 350,000 |

*Figure II-34: Pilot Hole Construction Phase Inputs*

Phase 2 inputs are shown in Figure II-24. The cost items are divided into 4 sections: conductor section inputs, deep drilling inputs, surface section inputs, and repository section inputs.

| | |
|---|---|
| **Conductor Casing Installation** | |
| All in Cost ($) | $ 25,000 |
| **Deep Drilling Costs** | |
| Mob + Demob Cost | $ - |
| Drill Rig Day Rate ($/d) | $ 35,000 |
| **Surface Section** | |
| Set-up Days | 1 |
| Length of Surface Section (m) | 280 |
| Drilling Production Rate (m/d) | 50 |
| Drilling Days (d) | 6 |
| Casing Unit Cost ($/m) | $ 1,000 |
| Cement Unit Cost ($/m) | $ - |
| Casing Installation Time (d) | 3 |
| Surface Section Cost ($) | $ 630,000 |
| **Repository Section** | |
| Length of Repository Section (m) | 700 |
| Drilling Production Rate (m/d) | 50 |
| Drilling Days (d) | 14 |
| Casing Unit Cost ($/m) | $ - |
| Concrete Unit Cost ($/m) | $ - |
| Casing Installation Time (d) | 0 |
| Rig Takedown (d) | 1 |
| Repository Section Cost ($) | $ 525,000 |

*Figure II-35: Phase 2 of Construction Inputs*

The conductor casing installation (drilling and casing) is inputted as a lump sum. The construction operations for the conductor setting is expected to be significantly different the construction of the rest of the repository borehole which will be modelled using daily rates and material rates.

Deep drilling costs sections allows for input of mobilization/demobilizations and a daily rate. The mobilization/demobilization allows for the input of a one-time cost item regardless of the total number of boreholes. The daily rate is the cost of having the drill rig on site (working or on stand-by) for the duration of construction.

The surface section allows inputs for: set-up days (days setting up the drill rig), the estimated drilling production rate (per day), the casing and cement cost per meter, and number of days to install casing.

The repository section has similar inputs compared to the surface section. The only difference is there is no input for rig set-up, instead it is labelled as rig takedown (assumed to be the time required to move the rig to the next borehole locations).

<u>Base Case Cost Estimate</u>

Using the inputs shown in the preceding section, a base cost estimate was developed. A 1 km deep borehole scenario was assumed. The authors used their experience in various drilling operations to develop estimates for all required inputs. These values are simplified and will likely vary once a final design is developed and engagement with local contractors and suppliers is undertaken. The breakdown of the base case cost estimate is shown in Figure II-25.

| | | |
|---|---|---|
| **Borehole Summary** | | |
| Number of Boreholes | | 1 |
| **Pilot Hole Cost** | $ | 350,000 |
| **Repository Hole Construction** | | |
| Moblization and Demoblization Costs | $ | - |
| Conductor Casing Construction | $ | 25,000 |
| Surface Section Construction | $ | 630,000 |
| Repository Section Consturction | $ | 525,000 |
| **Repository Hole Cost** | $ | 1,180,000 |
| **Overall Construction Cost** | **$** | **1,530,000** |

*Figure II-36: Base Case Cost Estimate for Drilling*

<u>Sensitivity Analysis for Drilling Cost Model</u>

A sensitivity analysis was completed on the following parameters: daily drilling rate, rate of penetration (assumed to be constant for both the surface and repository section), and the depth of the surface casing section.

*Daily Drilling Rate:*

The daily drilling rate was varied from $25,000 to $65,000 per day (with $35,000 per day used as the baseline estimate). Figure II-26 shows the affects of the daily rate on the overall cost of the drilling.

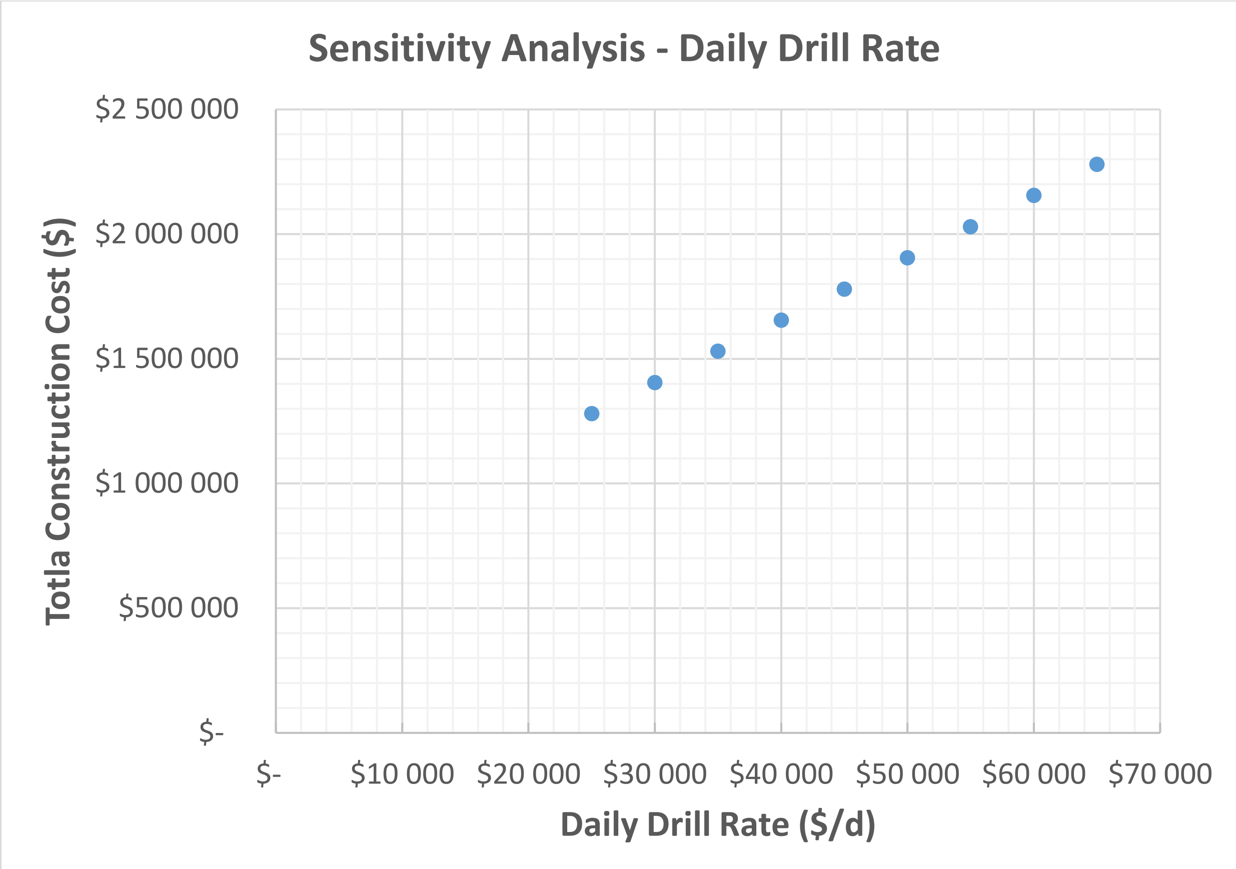


*Figure II-37: Sensitivity Analysis for Daily Drilling Rate*

The results of the sensitivity analysis showed a linear change in overall project cost with a change in daily drilling rate. For every $5000 per day increase in cost the overall cost of the project increased ~8%.

*Rate of Penetration:*

The rate of penetration (ROP) of the drill in meters per day was varied from 25 m/d to 120 m/d (with the base case of 50 m/d used). Figure II-27 shows the results of the sensitivity analysis for the ROP.

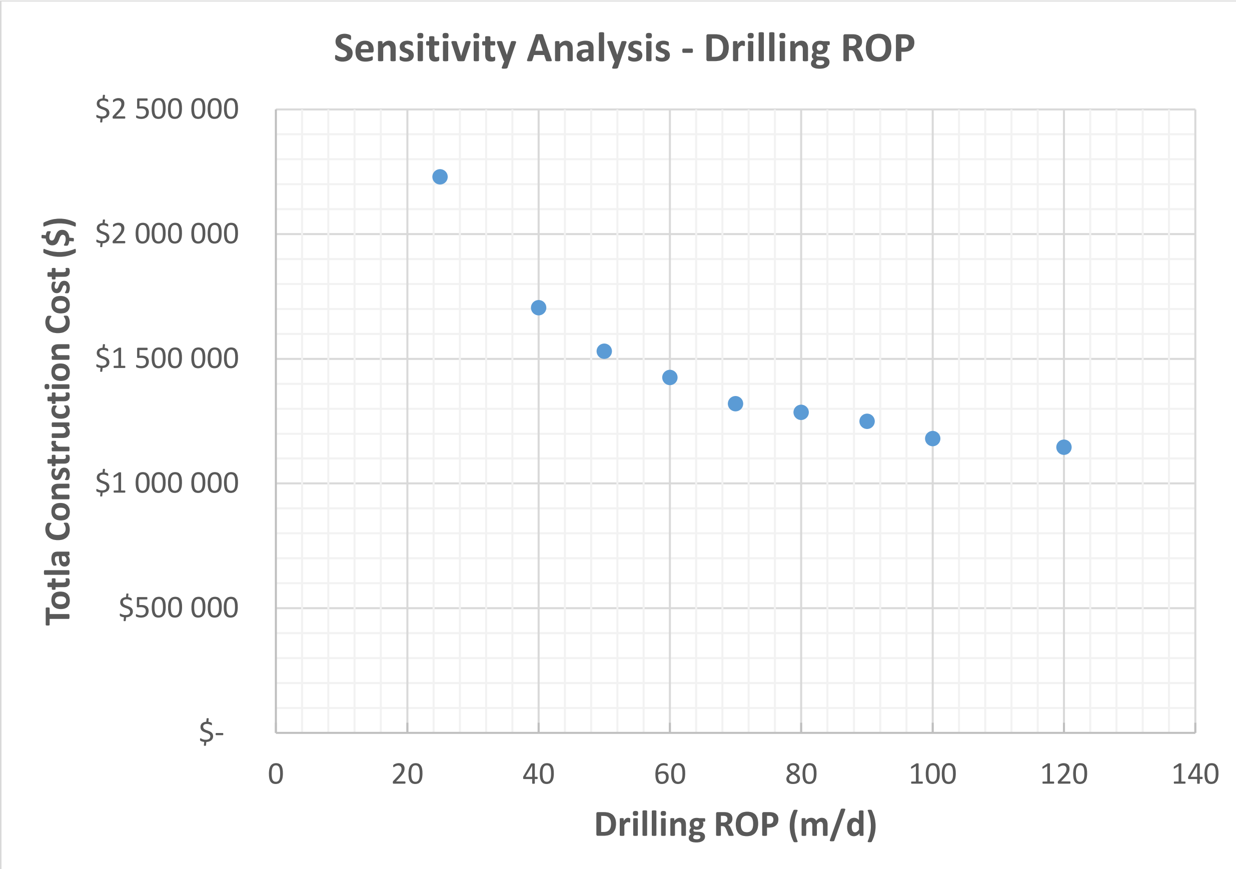


*Figure II-38: Sensitivity Analysis for Drilling ROP*

The sensitivity analysis shows a non-linear response of overall project cost to changes in the drilling ROP. For a 25 m/d rate of penetration, the overall project cost increases 46% above that of the baseline cost estimate (50 m/d). However, doubling the rate of penetration (100 m/d) results in a savings of ~23%. Further increases in ROP above 100 m/d have negligible impact on the overall drilling costs for this scenario.

*Depth of Surface Casing:*

The depth of the surface casing section was varied from 150 m to 550 m (with the base scenario being 300 m). Figure II-28 shows the result of the sensitivity analysis for depth of surface casing.

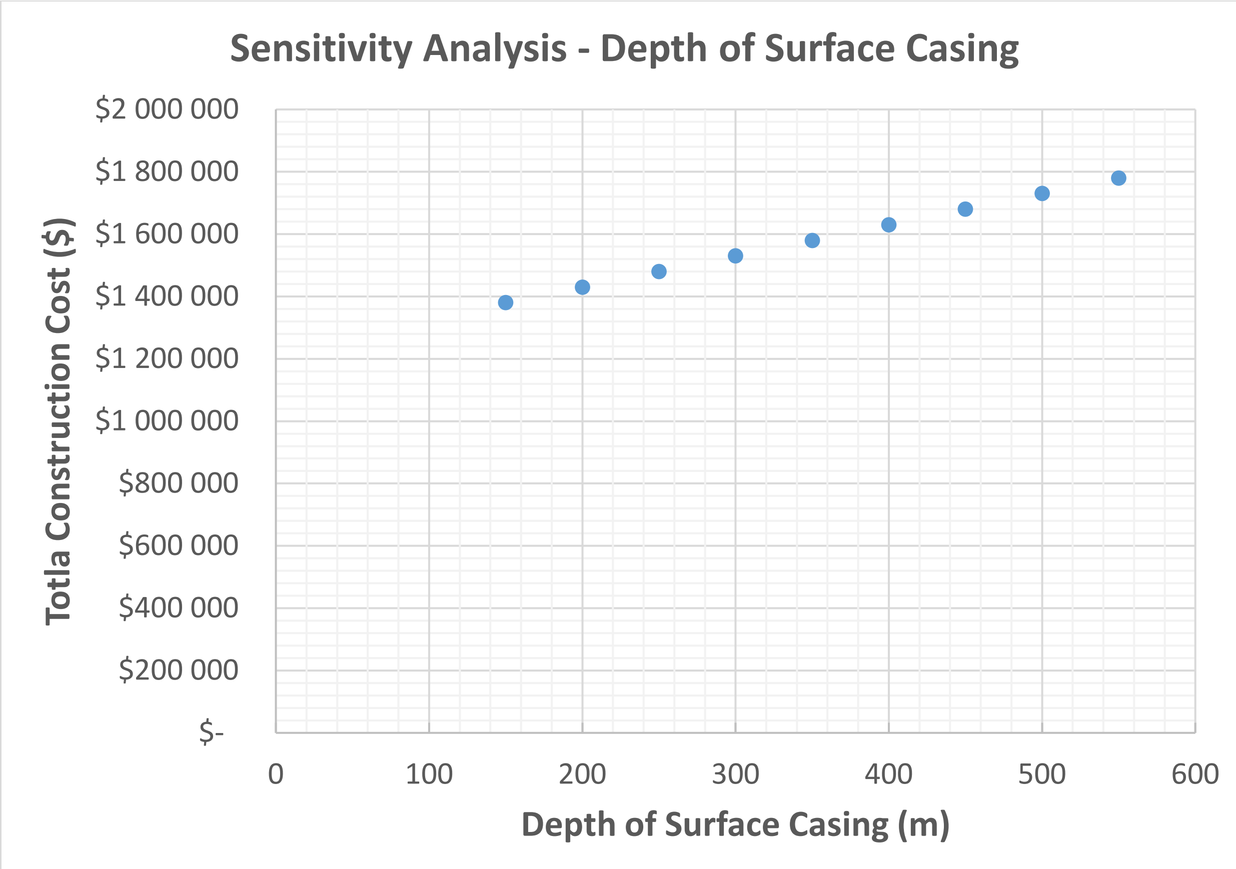


*Figure II-39: Sensitivity Analysis for Depth of Surface Casing*

The results show that changes to depth of the surface casing have a linear relationship with the drilling cost. For every 50 m of additional depth below 300 m resulted in a ≈3% change in overall drilling costs for the project.This blank page is the final page of the report.